NATIONAL BUREAU OF STANDARDS REPORT

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THROUGH DECEMBER 31, 1957

ON

STANDARDS FOR MECHANICALLY-REFRIGERATED ENCLOSURES

HEAT TRANSFER AND OTHER MEASUREMENTS DURING LABORATORY
AND ROAD TESTS OF REFRIGERATED SEMI-TRAILERS

by

C. W. Phillips
P. R. Achenbach
R. W. Penney

Report to
Transportation and Facilities Branch
Agricultural Marketing Service
U. S. Department of Agriculture
Washington, D. C.
and
Quartermaster Research and Engineering Command
Department of the Army
Natick, Massachusetts

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U. S. DEPARTMENT OF COMMERCE

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C. W. Phillips and P. R. Achenbach
Air Conditioning, Heating and Refrigeration Section
Building Technology Division, National Bureau of Standards
and
R. W. Penney
Transportation and Facilities Branch
Agricultural Marketing Service
U. S. Department of Agriculture

to
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Introduction

Culminating more than two years of planning and preliminary investigation of a satisfactory method for rating the heat transfer of refrigerated semi-trailers, several industry organizations and government agencies jointly sponsored a study by the Air Conditioning, Heating and Refrigeration Section of the National Bureau of Standards. The objective of this study is the development of a standard rating method for determining the heat transfer of these vehicles, by means of laboratory tests, so that the performance under road conditions can be predicted.

The Truck-Trailer Manufacturers Association, acting as coordinator for the industry sponsors, entered into a contract with the Transportation and Facilities Branch, Agricultural Marketing Service, U. S. Department of Agriculture, which, in turn, sponsored the necessary research and development work by the Air Conditioning, Heating, and Refrigeration Section at the National Bureau of Standards. The initial phase of the study was scheduled for completion by June 30, 1958, and commenced about the first of July, 1957.

Among the industry sponsors were:

> Truck-Trailer Manufacturers Association
> Truck Body and Equipment Association
> American Trucking Associations, Inc., Irregular Route
>   Common Carrier Conference
> American Trucking Associations, Inc., Equipment
>   Committee
> Individual trailer manufacturers
> Individual refrigerating unit manufacturers
> Individual component manufacturers.

Cooperating Government Agencies:

> U. S. Department of Agriculture, Transportation and
>   Facilities Branch, Agricultural Marketing Service
> U. S. Army, Quartermaster Research and Engineering
>   Command

To advise the NBS in the conduct of the study a Steering Committee was formed of the following members:

Paul R. Achenbach
National Bureau of Standards

H. C. Brown, Jr.
American Society of Refrigerating Engineers
Technical Committee 1.7

J. C. Cahill
Bureau of Yards and Docks

R. J. Campbell
Quartermaster Research & Engineering Command

T. H. Christensen
Transportation Research & Engineering Command

Harry Eyler
Truck-Trailer Manufacturers Association

C. P. Hoffman, Jr.
American Trucking Associations, Inc.

J. B. Hulse
Truck-Trailer Manufacturers Association

H. D. Johnson
U. S. Department of Agriculture

C. W. Phillips
National Bureau of Standards

F. J. Reed
Air Conditioning and Refrigeration Institute

H. G. Strong
American Society of Refrigerating Engineers
Technical Committee 4.3

J. C. Winter
U. S. Department of Agriculture

W. H. Redit, Consultant to Steering Committee
U. S. Department of Agriculture

Paul R. Achenbach, Chief, Air Conditioning, Heating, and Refrigeration Section, NBS was named Chairman, and C. W. Phillips, of the same Section, was named Secretary. Two meetings of the Steering Committee have been held during the period covered by this report. Both were held at NBS, the first on July 26 and the second on September 30, 1957.

The principal objectives of this study, as outlined in the proposal originally presented to the Truck-Trailer Manufacturers Association, were fourfold:

1. Complete the development of the comparison type heat sink method for rating the heat transfer of refrigerated trucks and trailers.

> Note: The National Bureau of Standards had previously designed and constructed a prototype "metering or comparison heat sink apparatus" for measuring heat transmission of trailers under normal direction of temperature gradient and had shown that the reverse heat flow method is not adequate when the outer skin of a trailer permits air and moisture infiltration.

2. Compare cooling load of several trailers in the laboratory using the metering heat sink method and on the road using a modified metering heat sink method.

3. Correlate and revise laboratory method in light of field results to adequately account for wind factor and solar radiation.

4. Provide information on air leakage and moisture transfer processes in refrigerated trailers looking toward improved insulating and vapor-sealing methods.

The principal tasks necessary to attain these objectives were outlined as follows:

I. Construct prototype metering heat sink to be used as a pattern for industry standard apparatus including instrumentation.

II. Prepare sketches, drawings, diagrams and operating instructions for building standard apparatus.

III. Prepare instruction manual on instrumenting specimen trailers and making performance tests.

IV. Prepare a test facility to permit testing of 35-ft trailers or trucks in ambient conditions of 100F dry bulb and 50 percent relative humidity.

V. Develop a method for simulating the road infiltration of air and moisture in a laboratory test.

VI. Measure cooling load of three trailers in laboratory using metering heat sink method under standard ambient and interior conditions.

VII. Modify a trailer refrigerating unit for measuring cooling load of trailers during road tests.

VIII. Measure cooling load of same three trailers under summer conditions on the road at road speeds of 30 mph and 50 mph.

IX. Correlate road test data and laboratory cooling load data.

X. Modify laboratory tests to adequately simulate solar load and air infiltration existing under road conditions.

The subsequent sections of this report cover the various major aspects of the tasks carried out during the reporting period, and are further identified as follows:

1. Preparation of laboratory.
2. Preparation of equipment for road tests.
3. Description of trailers tested.
4. Laboratory test procedures and test results.
5. Road test procedures and test results.
6. Comparison of laboratory and road test results.
7. Air infiltration.
8. Discussion and conclusions.

1. Preparation of Laboratory

A suitable structure in which to conduct laboratory tests of 35-foot refrigerated semi-trailers was assigned to the project by the National Bureau of Standards. The test structure on the Bureau grounds in Washington, D. C., is a lean-to type addition to a permanent concrete block building and its exterior surfaces are composed of corrugated metal sheathing. See Fig. 1, which shows, beside the building, some of the vehicles involved in the reported tests. The floor of the structure is concrete. To insulate the roof three-inch batts of fibrous insulation were placed between the rafters and held in place with corrugated aluminum sheets. After the roof insulation was installed, the inside height of the test space was approximately 15 feet on the low side of the sloping roof and 17 feet on the high side. Fig. 2 shows the interior of the structure during modification. The outer walls of the chamber consist of corrugated metal sheathing attached to each side of two-inch by six-inch wood studding, and the space between is filled with blown rock wool insulation. A sliding, overhead type door 12 feet wide and 14 feet high was installed at one end of the test room to provide a means for moving semi-trailers into the space. At the opposite end of the chamber an adjoining room approximately 11 feet square with a window and an outside door, was utilized as a control room and was equipped with suitable controls and instruments for conducting the laboratory tests. Fig. 3 shows the instrument panel. A door with a glass panel
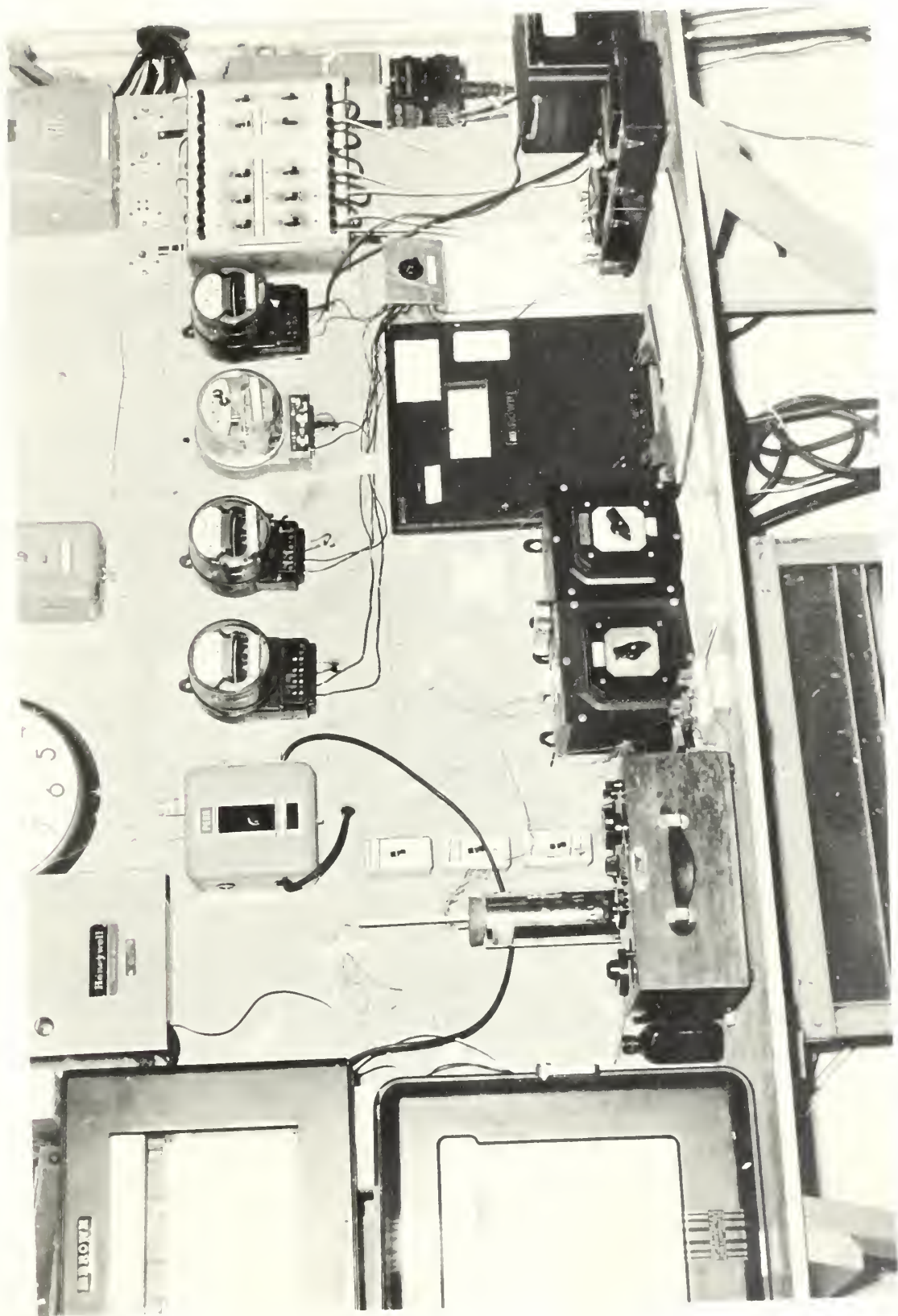
figure 1
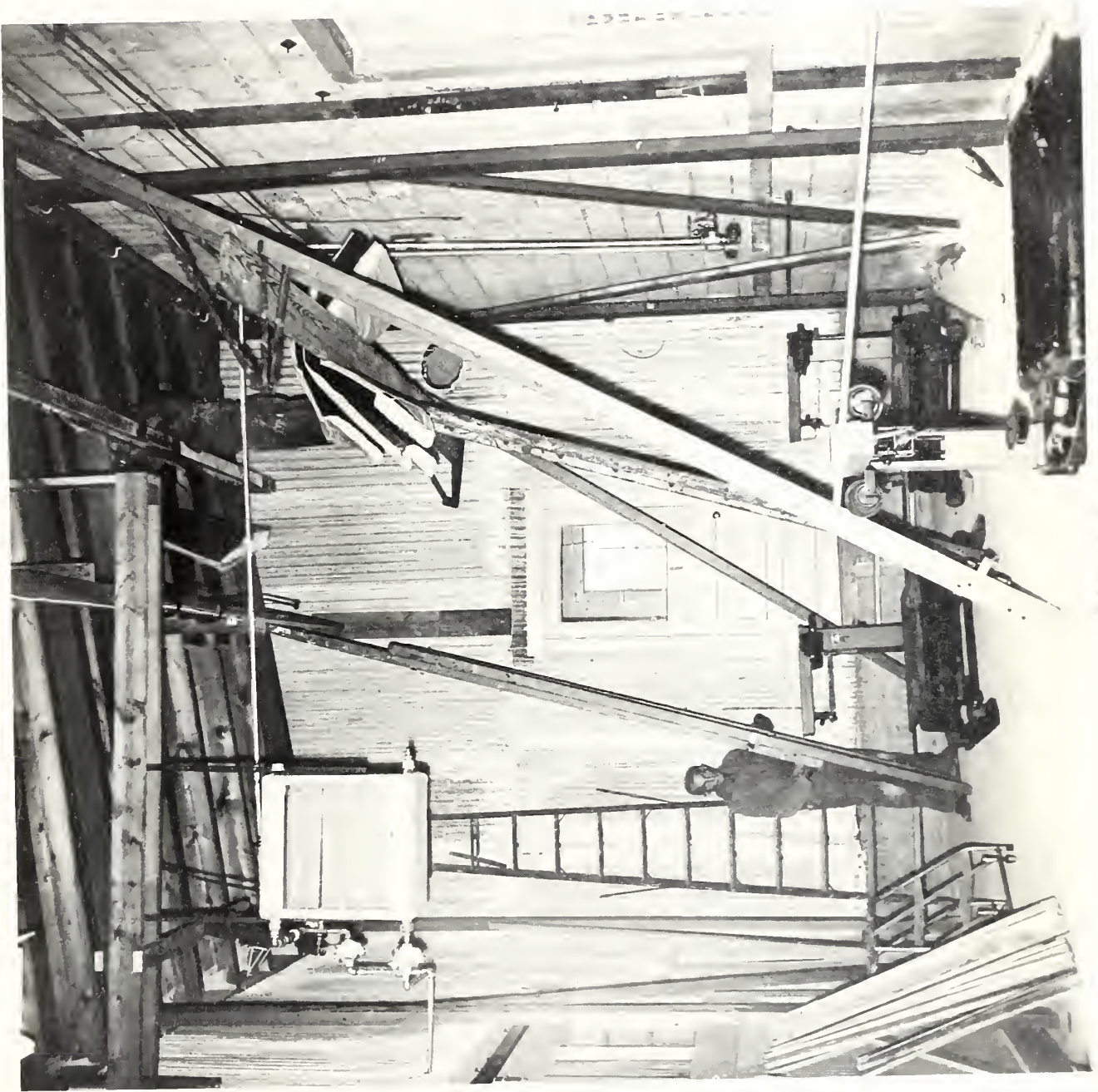
Figure 3

in the upper half connecting the two spaces was used to admit personnel into the test chamber during tests and was also used for observation. Near the north end of the outside wall of the test space, a pair of sliding doors approximately 12 feet wide and 8 feet high provided an opening for moving smaller equipment into the test room.

Additional electrical circuits were installed to provide the required electric power for lights, instruments, refrigerating equipment, etc., and steam lines were extended to serve two thermostatically-controlled space heaters for heating the ambient air, and both manual and automatic valves to introduce live steam into the area for humidification.

A prototype comparison heat sink apparatus consisting of sectionalized, semi-portable, refrigerating equipment which had been assembled for, and used in conjunction with, previous tests of smaller refrigerated semi-trailers in another test laboratory at NBS was installed outside the test chamber in a space approximately 23 feet, 8 inches long by 4 feet, 8 inches wide. The outer side of this space was enclosed with wooden framing and corrugated metal sheathing. The ends were left open and overhead protection was provided by the overhang of the test chamber roof.

This refrigeration equipment consisted of three electrically driven, two-speed compressors with water cooled condensers, two brine chillers, a brine pump, and a metered heat comparator. Fig. 4 shows the primary refrigerant and brine circuits of this equipment in schematic form. An enclosed self-contained cooling tower was installed to cool and recirculate the condenser water. Refrigerants 12 and 22 were used as primary refrigerants, and methylene chloride was used as the brine or secondary refrigerant.

For the laboratory tests a refrigeration coil with an integral blower (see Fig. 5) was placed in the trailer with the blower at approximately the same height above the floor as the blower of typical trailer-refrigerating units. A shielded electric space heater with built-in fan was placed on the housing of the cooling coil to assist in maintaining the

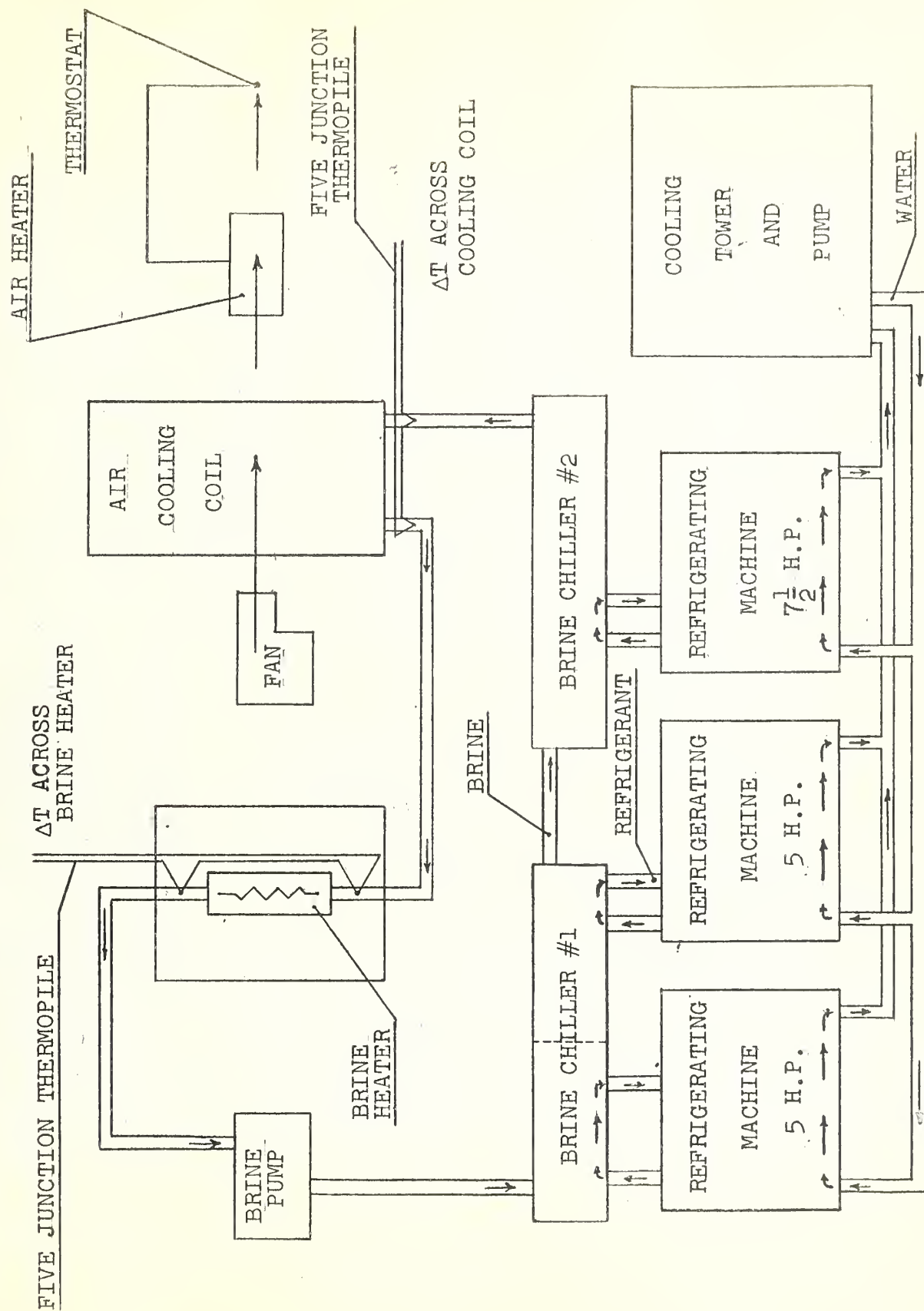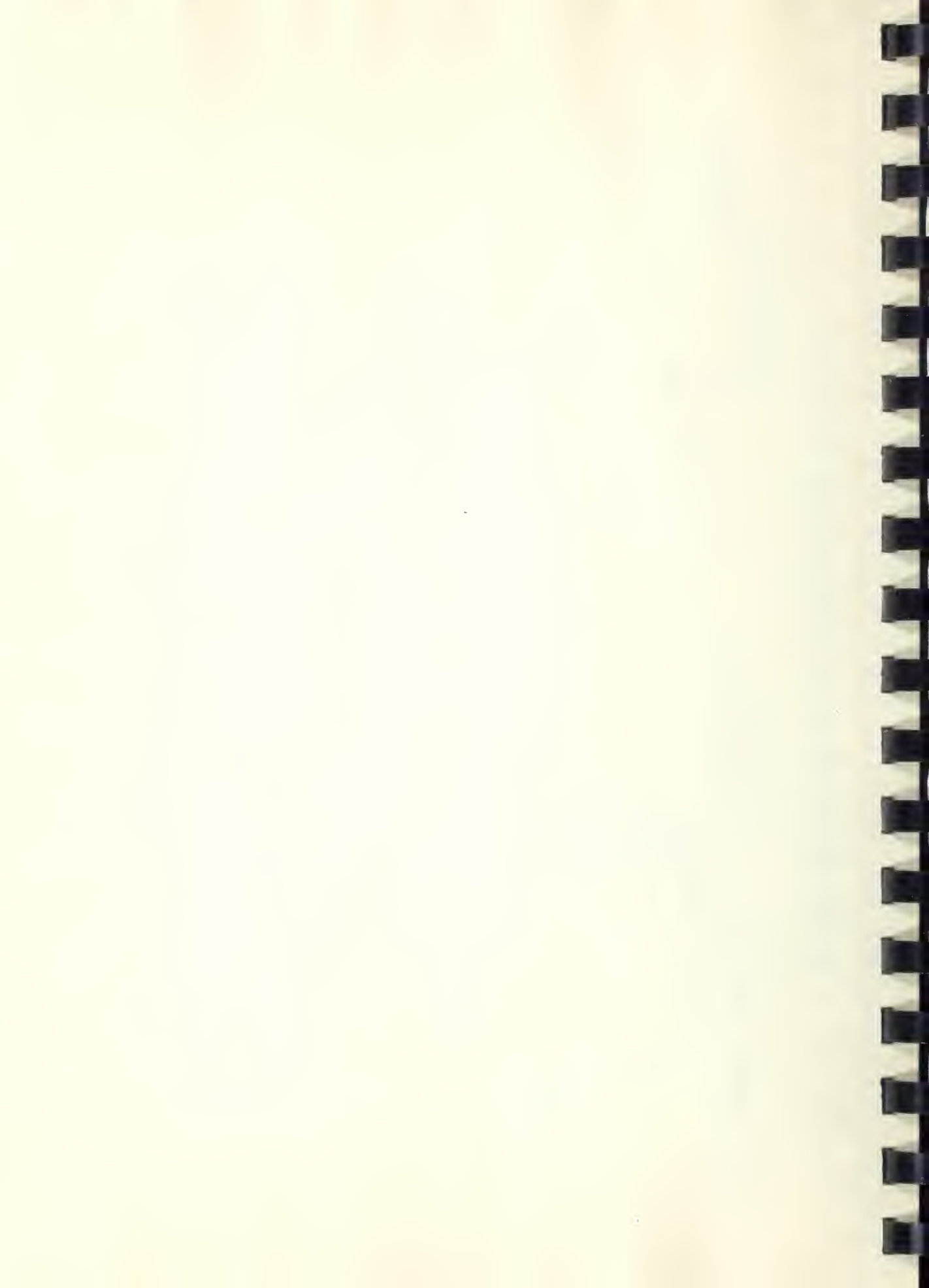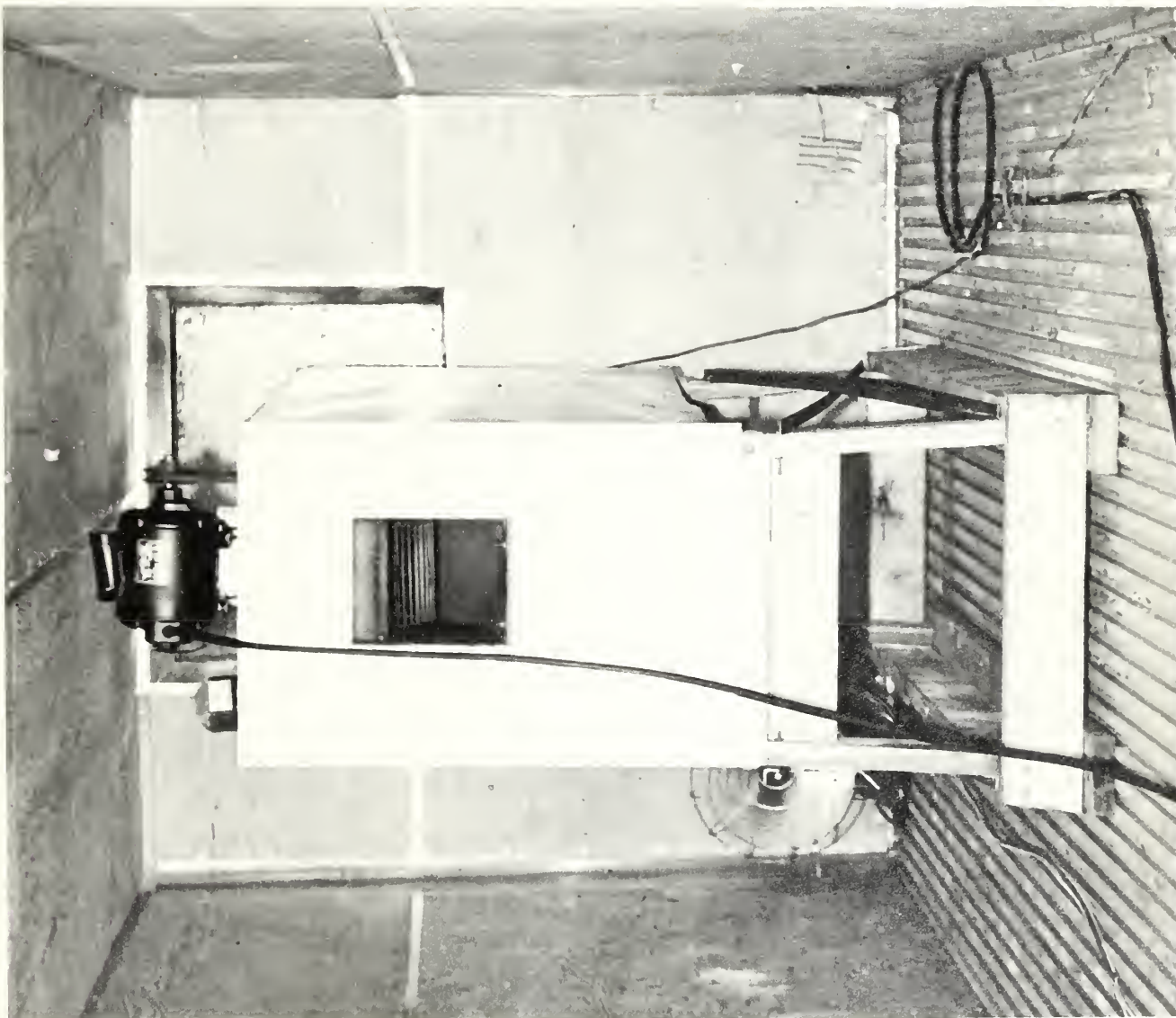REFRIGERATING CIRCUIT OF LABORATORY TEST EQUIPMENT
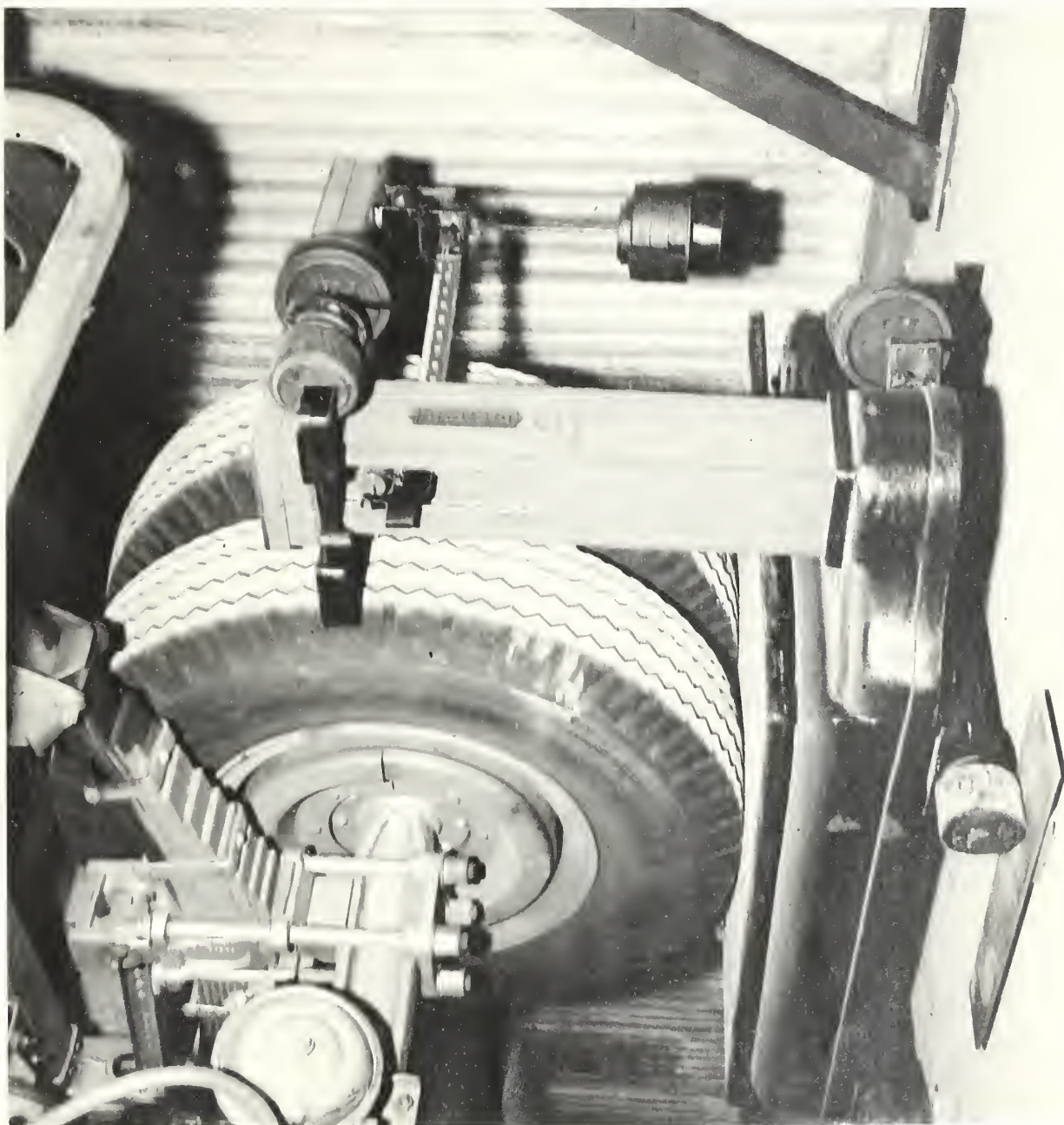

Figure 4

Figure 5

Figure 6

desired test temperature within the semi-trailer. The semi-trailer was backed into the test chamber and placed on three calibrated heavy-duty platform scales to determine the gain of weight caused by condensation of infiltrated moisture during the tests. Fig. 6 shows one of the three scales in place.

Copper-constantan thermocouples were installed inside and outside of each trailer as needed for control and measurement of temperatures. The inside temperature was determined by taking the average of twelve thermocouples positioned as follows: one in each corner of the front and rear of the trailer and one in each corner of a section midlength of the trailer. All of these thermocouples were in air about six inches from each adjacent surface. The test room temperature was determined by taking the average of eight thermocouples, one at each exterior corner of the trailer, installed in air not less than six inches from any adjacent surface. Numerous other thermocouples were installed for various test observations.

The methylene chloride brine lines were heavily insulated between the metered heat comparator and the refrigerating coil inside the trailer. The brine lines, the electric circuits to the fans and heaters, and the thermocouple extensions entered the trailer through a specially-designed, insulated wooden plug installed in the refrigeration unit opening in the front of the trailer.

Controls and equipment were set and adjusted to maintain the standard test conditions of OF temperature in the trailer, 100F ambient air temperature, and 50 percent relative ambient humidity. Six pedestal-type, 30-inch electric fans were used to circulate the ambient air around the trailer during the tests to promote uniformity of temperature and humidity. All temperature readings throughout the tests were made by means of thermocouples and either galvanometer or electronic potentiometers.

2. Preparation of Equipment for Road Tests

For road tests of the refrigerated semi-trailers, a tractor was provided, at a nominal rental, by the White Motor Company of Cleveland, Ohio. This vehicle was a Model

3024-PLT, tilt-cab over engine type of tractor and had a 127 1/2-inch wheel base. Fig. 7 shows the tractor before any modifications were made.

To equip the tractor for the road tests, it was necessary to mount various instruments within the cab and to install a gasoline-engine-driven generator and a two-piece, two-stage gasoline-engine-driven refrigerating unit immediately behind the cab.

To provide space for mounting the necessary test equipment the fifth wheel assembly on the tractor was moved backwards on the frame to a position directly over the single rear axle, and the twin 50-gallon cylindrical gasoline tank assembly, with platform, was moved approximately 40 inches toward the rear of the frame. The air brake hose column was also moved back. To support the gasoline-engine-driven generator and the two-stage gasoline-engine-driven refrigeration units, supports were fabricated and attached to the tractor frame in the space where the gasoline tanks and platform had been. These supports consisted of two 80-inch lengths of 4-in. x 1 1/2-in. steel channel sections each welded edgewise to a pair of 3-in. x 10-in. x 3/8-in. steel bearing plates, so spaced as to rest upon the upper part of the channels comprising the sides of the tractor frame. To prevent side motion, two 11-inch lengths of 2-in. x 2-in. steel angle sections were welded to the outer edge of each bearing plate and to the channels so that they would extend downward outside the frame of the tractor. These supports were placed laterally across the tractor frame and spaced on 30-inch centers. They were secured to the tractor frame by means of bolts through the angle irons and through the frame. Existing bolt holes in the frame were utilized wherever possible to prevent weakening the tractor frame by drilling unnecessary holes in it. No holes were drilled in other than the tractor frame web. Adequate bracing was provided for the overhanging portion of the channels by welding diagonal lengths of angle iron to the channel and to the angle irons attached to the outside of the tractor frame. Two steel tool boxes were mounted, one on each side, under the overhanging frame supports.

Figure 7

A gasoline engine generator capable of continuous loading at 2.3KVA was placed on the left side of this supporting frame, and the two sections of the gasoline-engine-driven refrigerating unit were placed one above the other on the right side. Each of the three auxiliary gasoline engines driving these units received its gasoline supply from the tractor tanks. These units supplied the electric power and the primary refrigeration used during the road tests.

Fig. 8 is a view of the left side of the tractor showing the engine generator, tool box and gas tank, and Fig. 9 shows the two-piece refrigerating unit, tool box, and gas tank on the right side. Note the grouping of all of the cables, thermocouples, and flexible refrigerant lines in a single flexible connection between the tractor and trailer. Air brake hoses and trailer lighting cables were not included in this grouping but were connected as in normal service.

The refrigerating unit was specially designed for this application by Tru Kooler, Inc., of Oelwein, Iowa, and consisted of a refrigerant-12 high stage and refrigerant-22 low stage section. Each stage was powered by a Wisconsin Model VH4D air-cooled engine. This unit was used to cool a secondary brine by means of a chiller which was mounted inside of each trailer under test. Fig. 10 shows schematically the arrangement of both the primary and secondary refrigerant circuits of the mobile equipment. Methylene chloride was used as the secondary refrigerant or brine. Fig. 11 shows the physical location of the refrigerating components as installed for the road tests.

To facilitate the installation of the brine chiller in each trailer for the road tests, it was placed inside a reinforced 3/4-inch plywood box 12 feet long, 28 inches wide and 24 inches high. It was securely positioned inside the box together with the necessary brine lines, primary refrigerant liquid lines, a heat exchanger, pressure equalizing tube, thermal expansion valve sensing bulbs and capillaries. The brine lines and the primary refrigerant liquid and suction lines were extended through the front end of the box and provisions made for the necessary external connections. A separate small
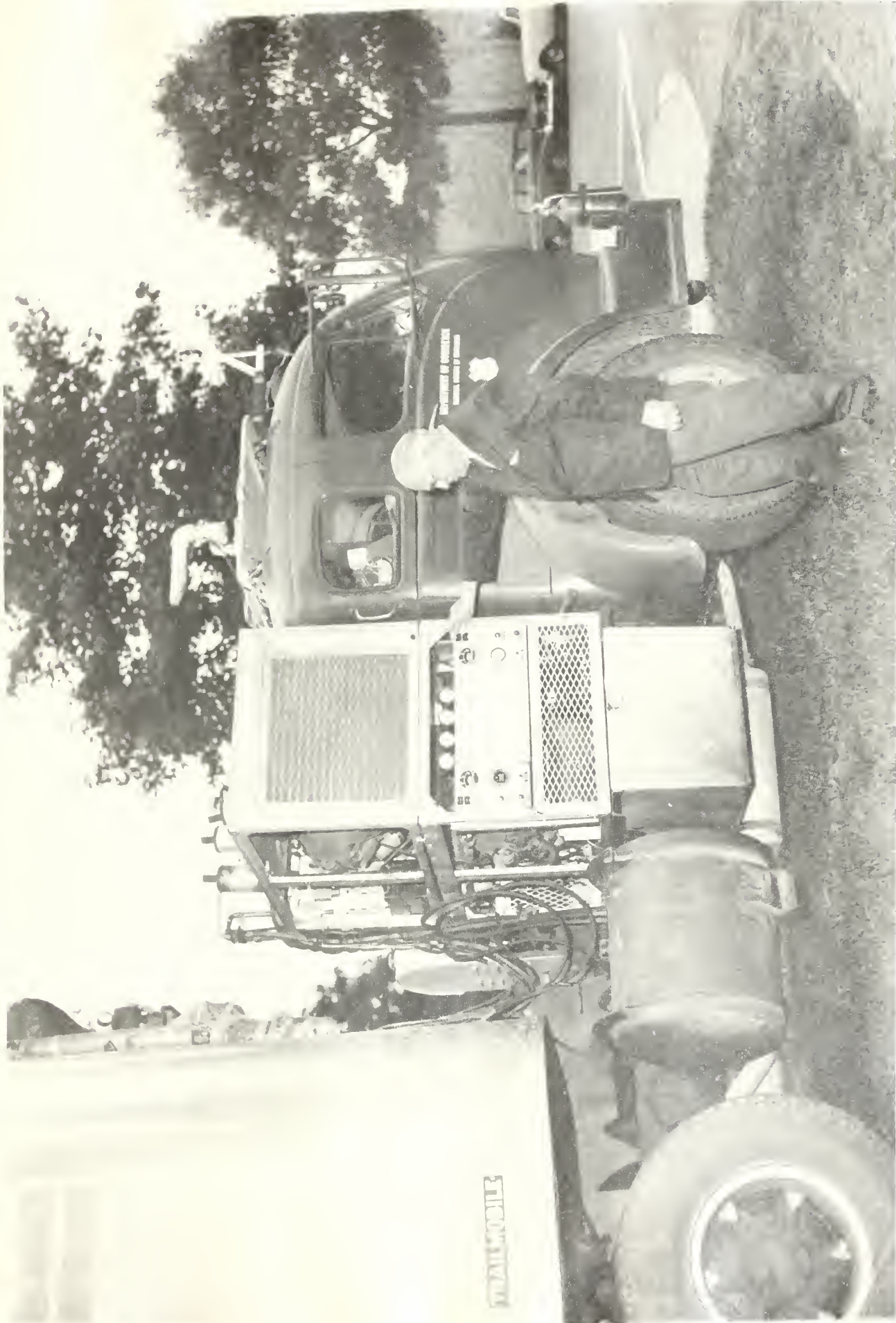
Figure 8

Figure 9

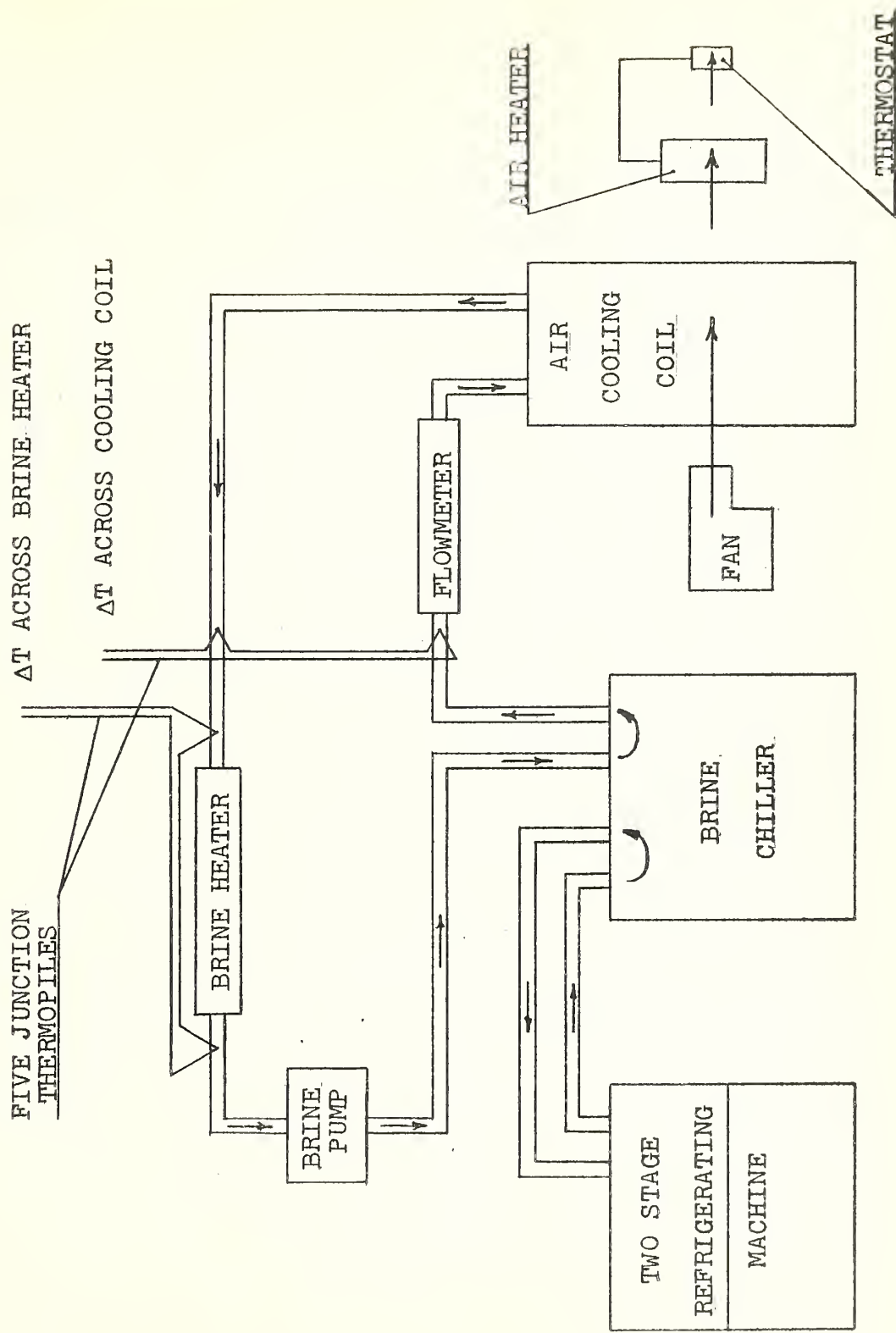REFRIGERATING CIRCUIT OF MOBILE TEST EQUIPMENT
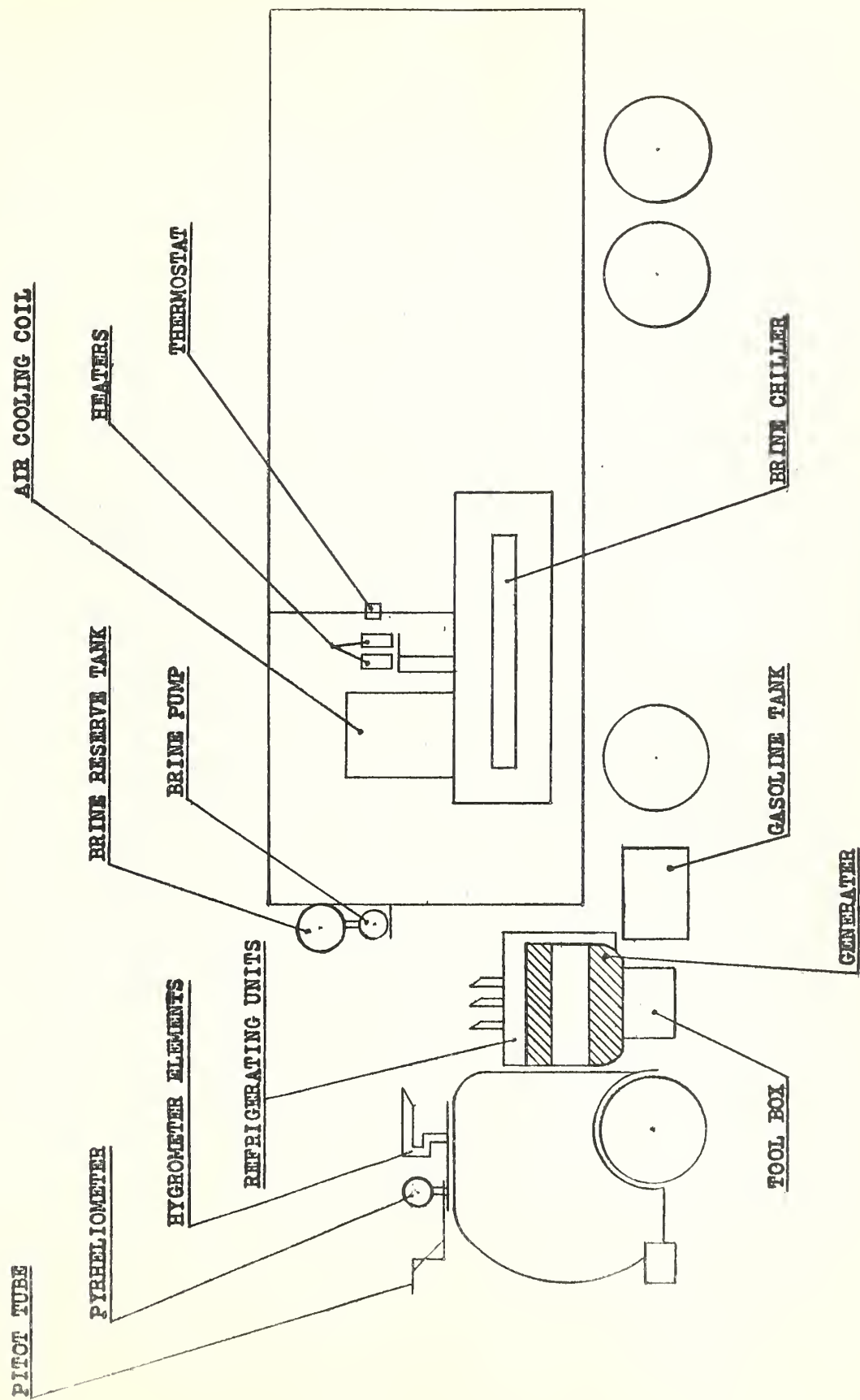

Figure 10

PHYSICAL LAYOUT OF MOBILE TEST EQUIPMENT

Figure 11

compartment was provided in the upper left-hand corner of the rear of the box to house the two thermal expansion valves. This valve compartment had an external plywood cover so that adjustments could be made to the valves without taking the lid off the entire box. After the necessary equipment was placed in the box, the space around the components was carefully packed with glass wool insulation. After the insulation was installed, the lid was placed on the box and secured.

A framework of 2-in. x 6-in. lumber was attached to the front portion of the chiller box and extended above it to support the air cooling coil for the trailer. This coil was mounted at such a height that the discharge from its built-in blower would be at about the same height above the floor as that from a typical trailer refrigerating unit. This cooling coil was rated at 17,500 Btu/hr at 0°F entering air, -10°F leaving air, 1750 cfm at 1/2-in. static pressure, -23°F entering brine (methylene chloride), -13°F leaving brine. It had a six-row, two-circuit brine coil with a pressure drop of 1.4 psi at 5.22 gpm. The galvanized casing of the coil measured 44 1/2 in. high, 52 1/4 in. long, and 28 5/8 in. deep. The blower motor was 1/3 hp 115/230 V, 1 phase, 60 cycle. An electric heater of about 600 watts capacity with a built-in fan was installed to assist in maintaining the desired trailer temperature. Fig. 12 shows the chiller, coil and heater assembly being placed in a trailer, and Fig. 13 is a view of the assembly after installation. It can be seen from these two figures that the brine chiller, the air cooling coil and the control heaters were assembled and installed in each test trailer as a unit. Included in the brine piping between the chiller and coil was the sensing element of an electronic flowmeter for measuring the flow of methylene chloride brine during the tests. This sensing element was connected to instruments mounted in the tractor cab. After the chiller assembly was installed in the trailer, brine line connections to and from the brine pump were made up, and the primary refrigerant liquid and suction lines were connected.
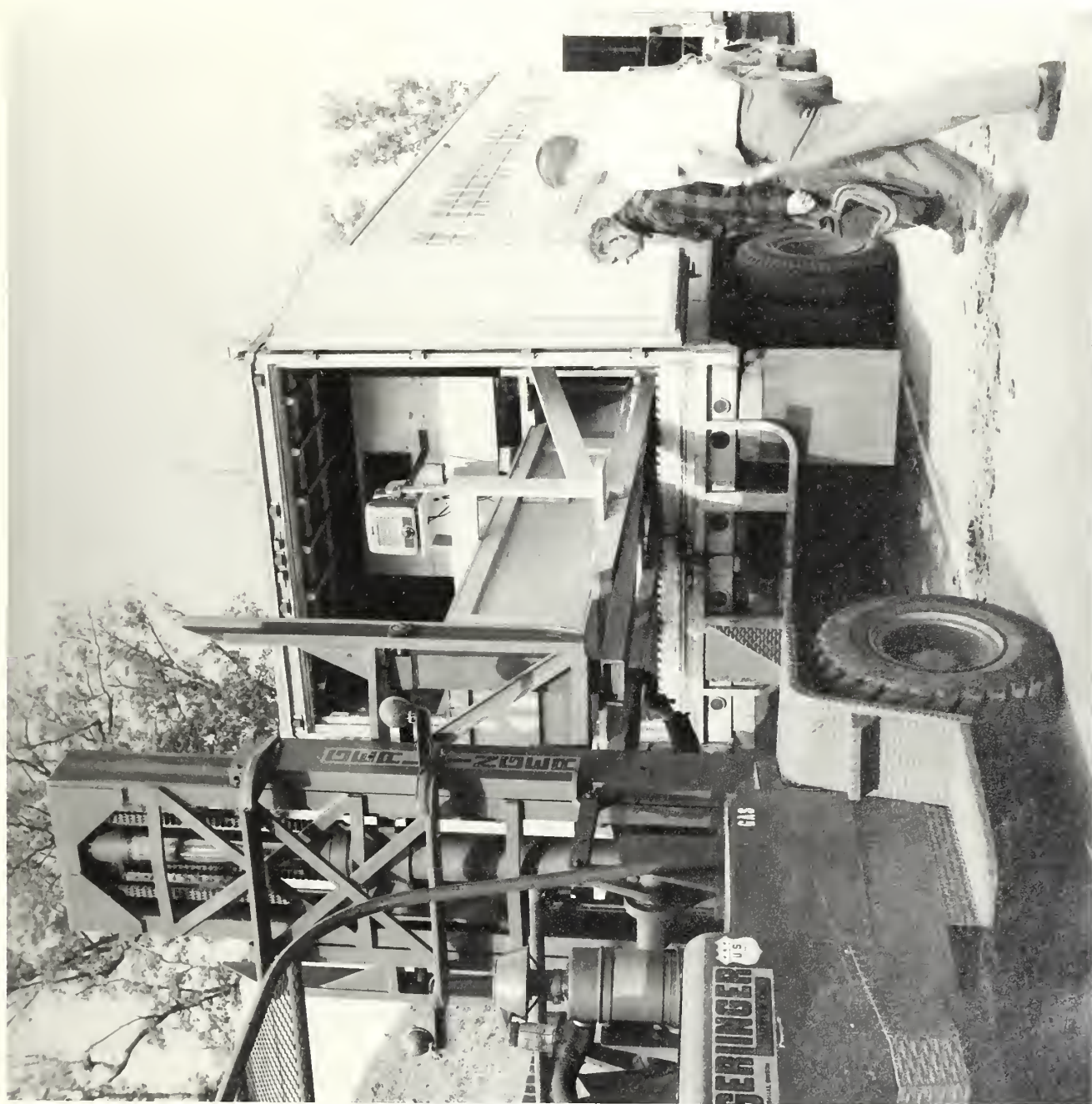
Figure 12

Figure 13

An aluminum faced, insulated wooden plug approximately five inches thick was placed in the refrigerating unit opening provided in the front of each test trailer. This plug was reinforced near its outer edges with angle iron and was provided with a steel shelf on its exterior surface on which was mounted an electrically-driven brine pump connected to brine lines extending a short distance beyond the inner face of the plug. A ten-gallon brine storage tank, for make-up and expansion, was also attached to the front face of this plug, above the pump and motor and was connected into the brine circuit at the pump inlet. The circulating pump, the storage tank, and the brine lines were insulated. On the right-hand edge of the plug a primary refrigerant heat exchanger was mounted to which the flexible primary refrigerant liquid and suction lines to the tractor-mounted refrigerating unit were connected. Provisions were also made in the plug for introducing thermocouple extensions, electric power and control circuits, and tubes for measuring air pressure differences into the inside of the trailer. Fig. 14 shows the arrangement of equipment on the plug.

Instruments mounted in the tractor cab can be seen in Fig. 15, and these instruments are identified in the sketch of Fig. 16. In addition to the normal instruments provided for operation of the tractor, the following instruments were provided in the cab:

1. Electronic indicating potentiometer, for readings of temperature, temperature difference, relative humidity, relative incident radiation, and brine flow rate.

2. Electronic recording potentiometer, for permanent record of each of the variables listed in item 1.

3. Recording speedometer, for permanent record of rate of speed and time of operation.

4. Clock for time.

5. Electric clock frequency meter, for observing performance of engine generator.
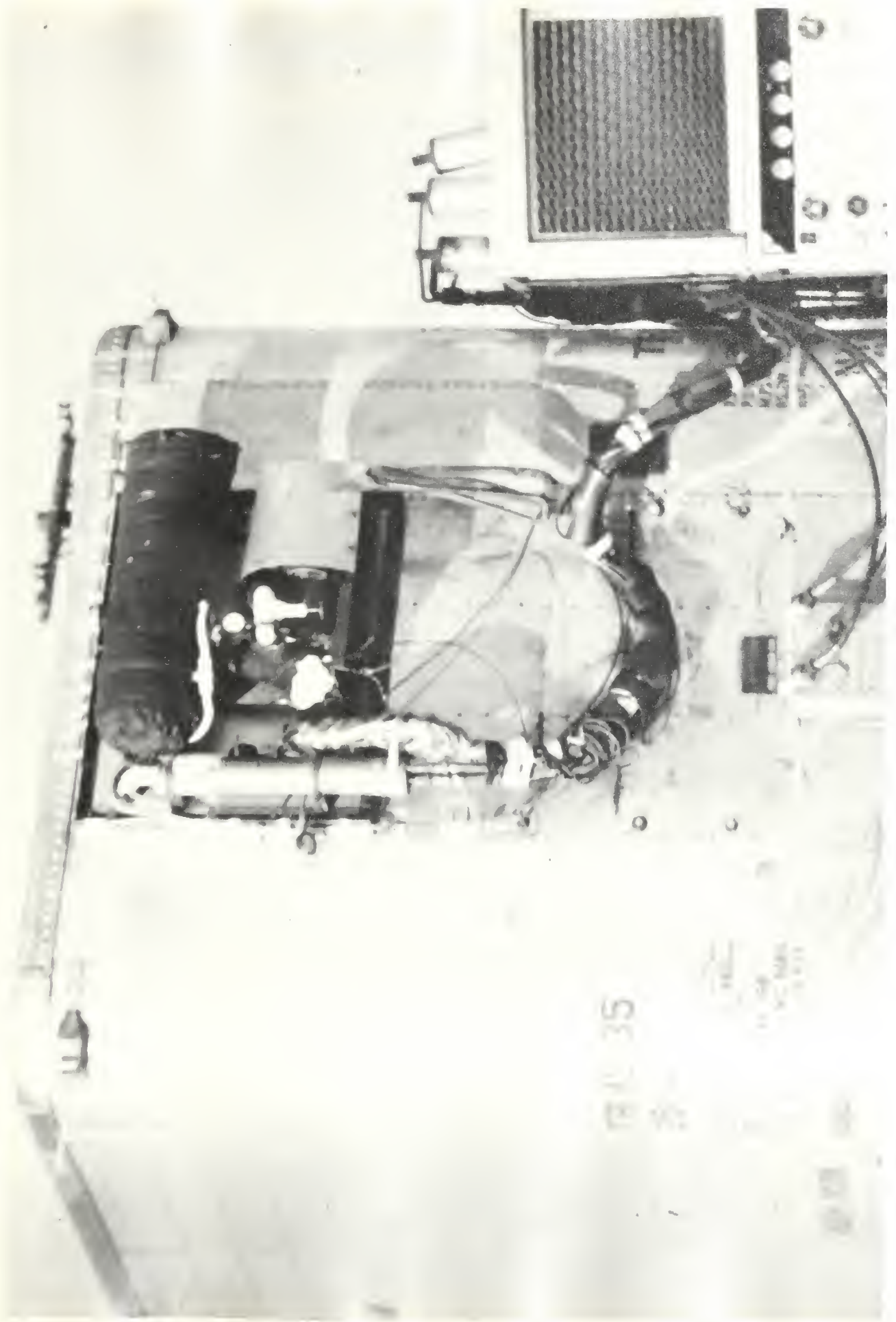
Figure 14

Figure 13

INSTRUMENT LOCATION FOR MOBILE TEST

BRINE FLOW TOTALIZER

ELECTRIC CLOCK

INSTRUMENT VOLTS

INDICATING POTENTIOMETER

MULTIPOINT RECORDER

RELATIVE HUMIDITY

BRINE FLOW RATE

GENERATOR AMPERES

GENERATOR VOLTS

WATT HOUR METER

TEMPERATURE CONTROL

STEERING WHEEL

REL. HUM. SEL. SW.

AIR PRESSURE GAGES

POTENTIOMETER SELECTER SWITCHES

HOT WATER AND ICE BATHS

POWER SWITCHES

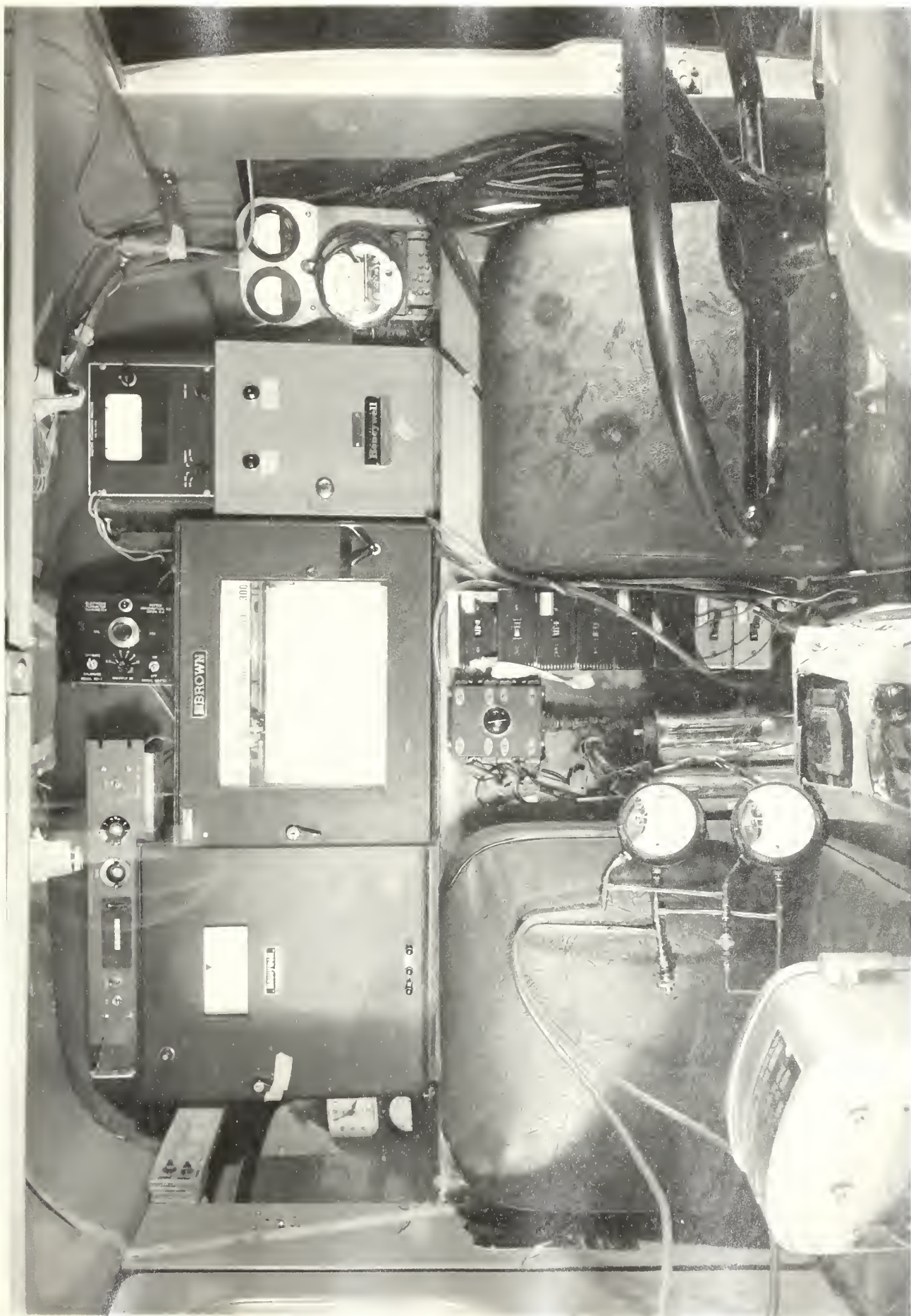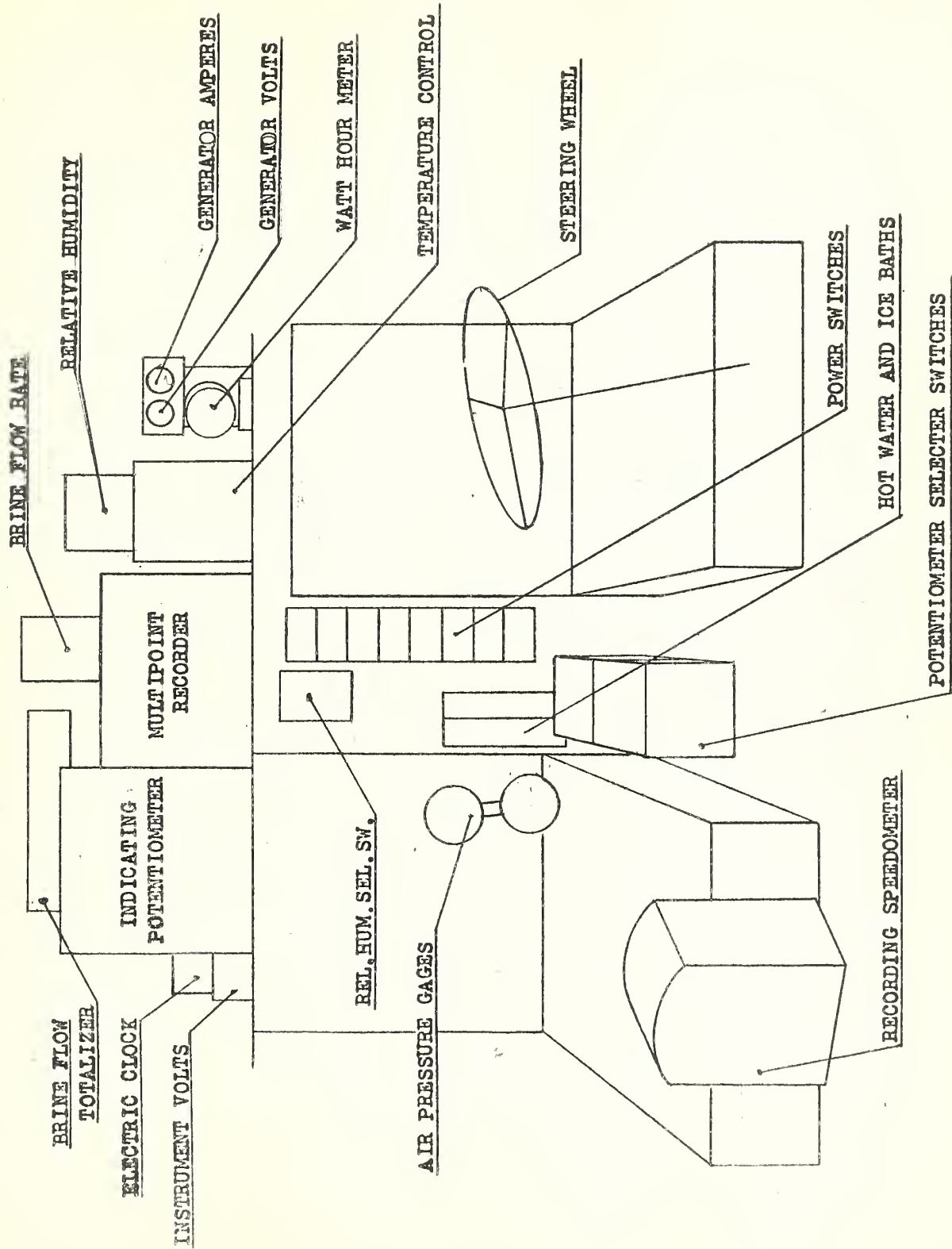RECORDING SPEEDOMETER

Figure 16

6. Ammeter and voltmeter, for observing electric generator output.

7. Watthour meter, for integration of power input to trailer.

8. Brine flow totalizer and frequency converter, for integrated flow and flow rate observation.

9. Electric hygrometer, for indication of ambient relative humidity.

10. Pressure gages, for measurement of impact and static air pressures.

11. Various switches, constant voltage transformer, hot and cold reference baths, etc.

Pyrheliometer (for measurement of relative incident radiation), Pitot tube (for measurement of impact and static air pressures during motion), and protective tube for the electric hygrometer elements were mounted on the cab roof, and may be seen in Fig. 17.

Figs. 18 and 19 show, respectively, right- and left-hand views of the tractor-trailer combination connected for operation.

3. Description of the Test Vehicles

Six trailers have been involved in the tests referenced in this report. Of these, three were commercial trailers and three were military vehicles. The three commercial vehicles, each described in more detail later in this section, were:

1. Fruehauf, new, 33 feet 6 inches long, loaned by the Fruehauf Trailer Company.

2. Trailmobile, new, 35 feet long, loaned by Trailmobile, Inc.

3. Fruehauf, used, 35 feet long, loaned by the Emery Transportation Company.
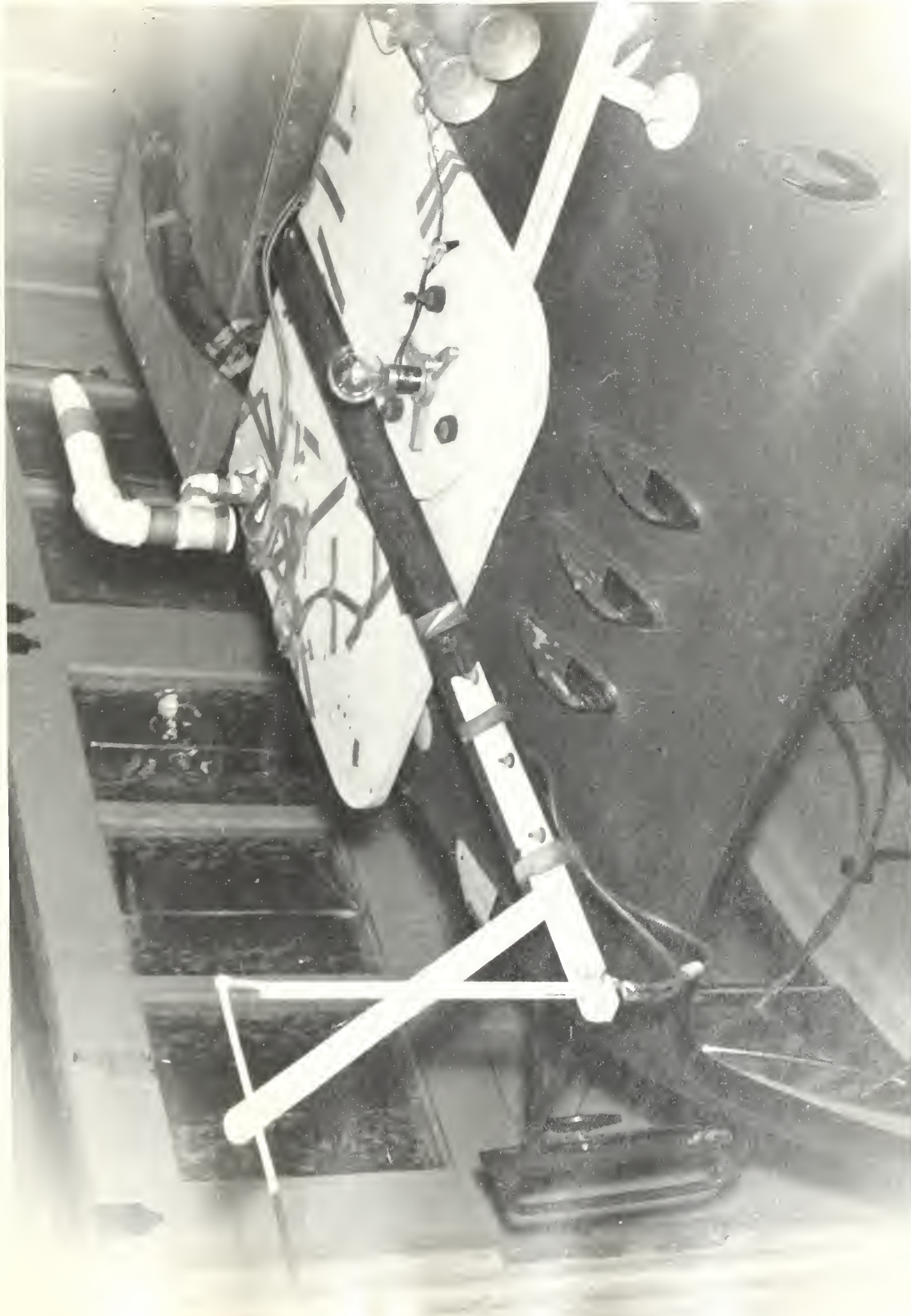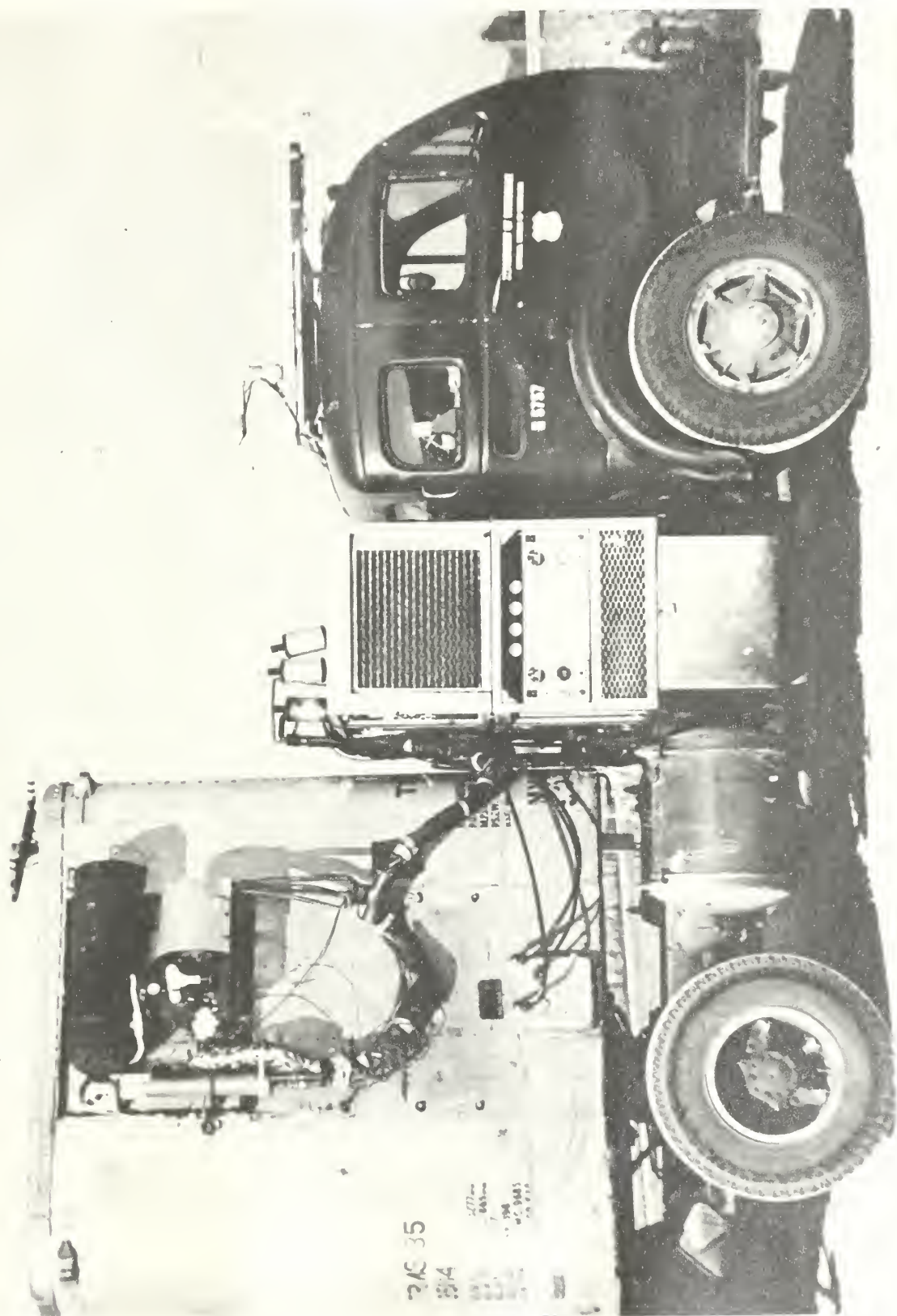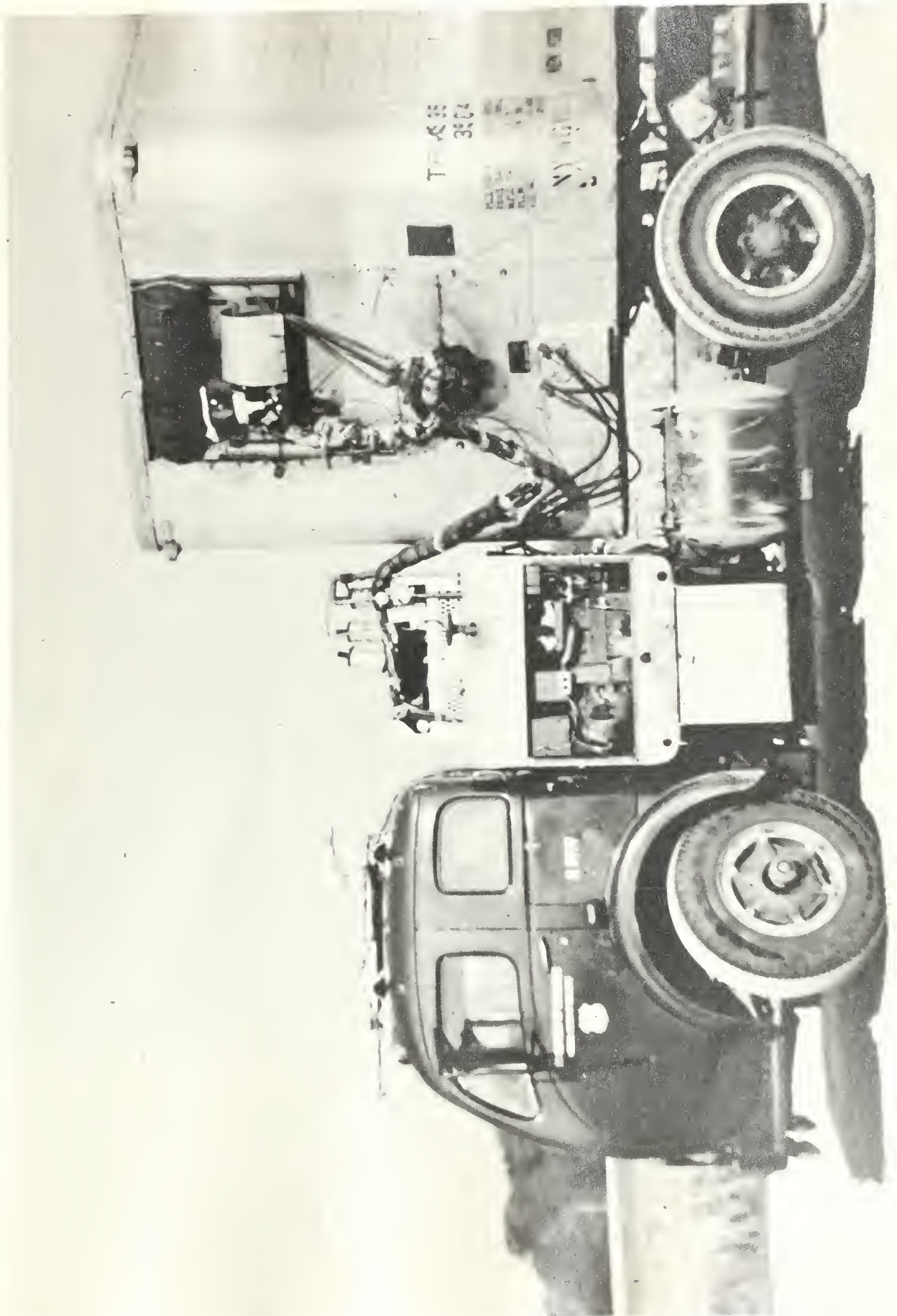
Figure 17

Figure 13

Figure 19

The three military vehicles were 7 1/2-ton, 21-foot, single-axle trailers manufactured to U. S. Army specifications, and were studied for heat transfer and moisture transfer characteristics by the National Bureau of Standards for the Quartermaster Research and Engineering Command prior to the tests of the commercial vehicles. Although the three vehicles differed slightly, Figs. 20, 21, and 22 show, respectively, the front, rear and interior of one which is typical. The comparison heat sink apparatus later modified for the laboratory tests of the three commercial vehicles was first developed by the National Bureau of Standards in order to study the effect of accumulation of ice or water in the insulation of one of these military trailers . One of these vehicles was used in the study of air pressures on the surfaces and in the insulation and cargo spaces during operation on the road at fifty miles per hour. They were also used for infiltration measurements prior to the tests of the commercial vehicles. None was used for road tests of heat transfer. The military vehicles had aluminum exterior and interior surfaces and had various forms of extruded or formed aluminum floors. Glass fiber insulation was used in the walls and roof, and expanded polystyrene was used in the floors, with six-inch insulation thickness in most cases. The empty weight was about 8,000 pounds.

The three commercial insulated semi-trailers were loaned for these tests by organizations interested in the development of a standard rating method and are described as follows:

I.   Fruehauf - New, from Fruehauf Trailer Company

The Fruehauf refrigerated semi-trailer furnished for laboratory and road tests was new and was loaned for the tests by the Fruehauf Trailer Company. The Model Number was SSVVR533-6 and the Serial Number was FW108753. It was a single-axle trailer as shown in Fig. 23. The overall length was 34 feet, 1 inch, the width 8 feet, and the height 12 feet. The body length of the trailer was 33 feet, 4 inches, the width 7 feet, 10 inches and the height 8 feet, all exterior dimensions. The inside length was 32 feet, 4 inches, the width 6 feet, 6 inches and the height 6 feet, 7 inches. The empty weight was 9,722 pounds.
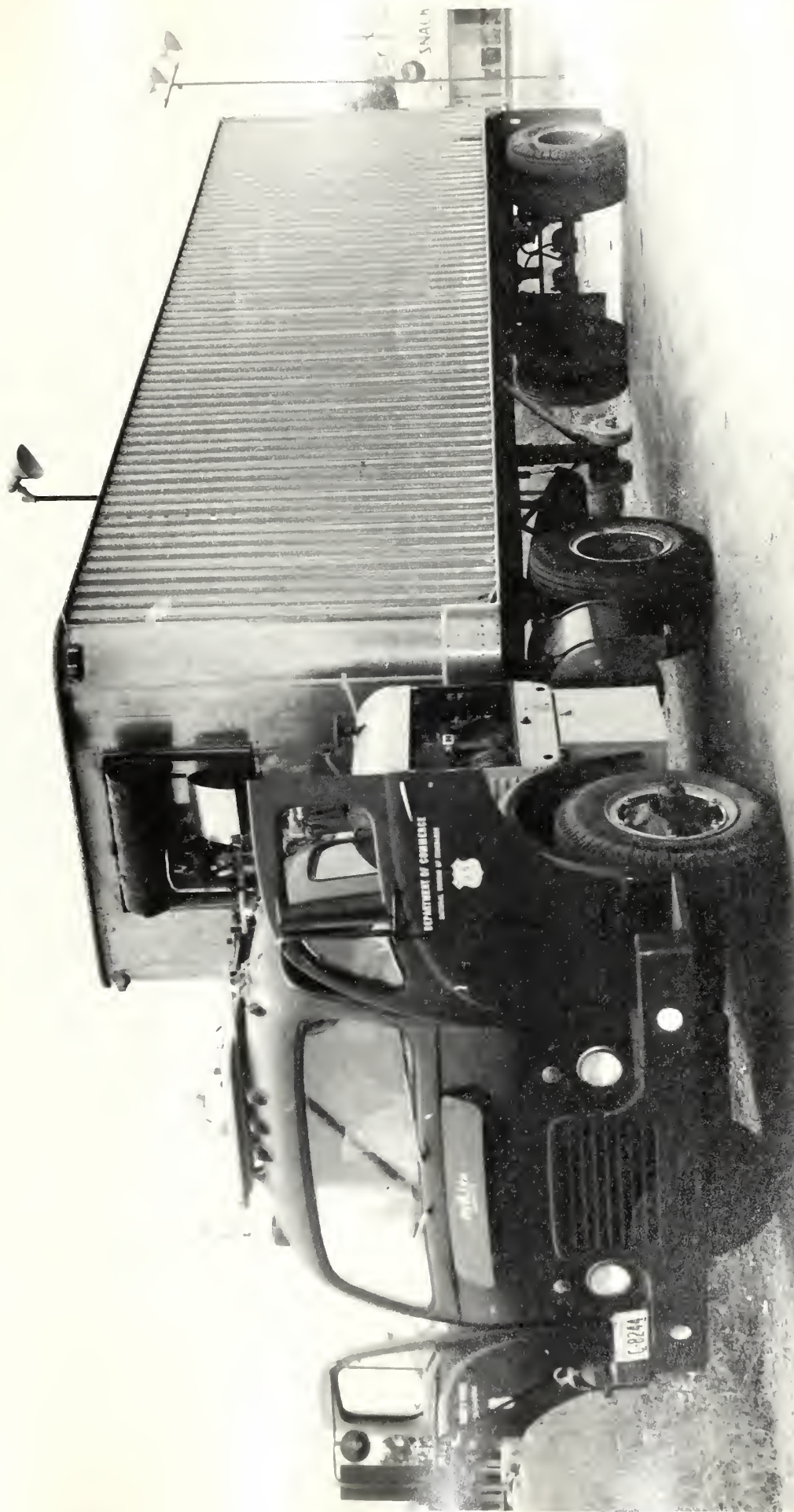
Figure 20

Figure 21

Figure 22

Figure 2.

The exterior skin of the trailer was stainless steel of spot-welded construction and the side walls were corrugated in the form of vertical channels with trapezoidal cross-section. These channels were 1 inch wide across the outer face, 1 3/4 inches across the base and the flat areas between the bases were 4 1/2 inches wide. The sides and ceiling were insulated with 6 inches of glass fiber insulation, and the floor with 5 inches of expanded polystyrene. The interior lining was plywood, and the floor was extruded, interlocking channel type aluminum alloy with integral flashing. There did not appear to be any vapor barrier in the walls or ceiling other than the exterior skin. There was a curbside door 4 feet, 4 inches wide at a distance 12 feet, 9 inches from the front of the body. There were no meat rails or bows in this trailer.

II.   Trailmobile - New, from Trailmobile, Inc.

The Trailmobile refrigerated semi-trailer was furnished for laboratory and road tests by Trailmobile, Inc., and was apparently in new condition. The Model Number was L-8225, and the Serial Number 6-01772-(35).

Fig. 24 is a view of this trailer.

The overall length was 35 feet, 5 inches, the width 8 feet, and the height approximately 12 feet. The outside body length was approximately 35 feet, the width 7 feet, 11 inches, and the height 8 feet, 5 inches. The inside body length was 34 feet, the width 6 feet, 11 inches, and the height 7 feet, 1 inch. The empty weight was 12,563 pounds.

The exterior skin was of riveted aluminum sheets and the interior lining was treated plywood. The walls and roof were insulated with six inches of glass fiber insulation; the floor with six inches of expanded polystyrene. There was no evidence of a vapor barrier other than the exterior skin, but the specifications indicated that all interior joints of the shell were to be sprayed with an undercoat. There were approximately 72 holes, 1/4-in. in diameter, in the upper lip of the side channels at the base of the walls. These holes communicated with the insulation space in the walls. The floor was
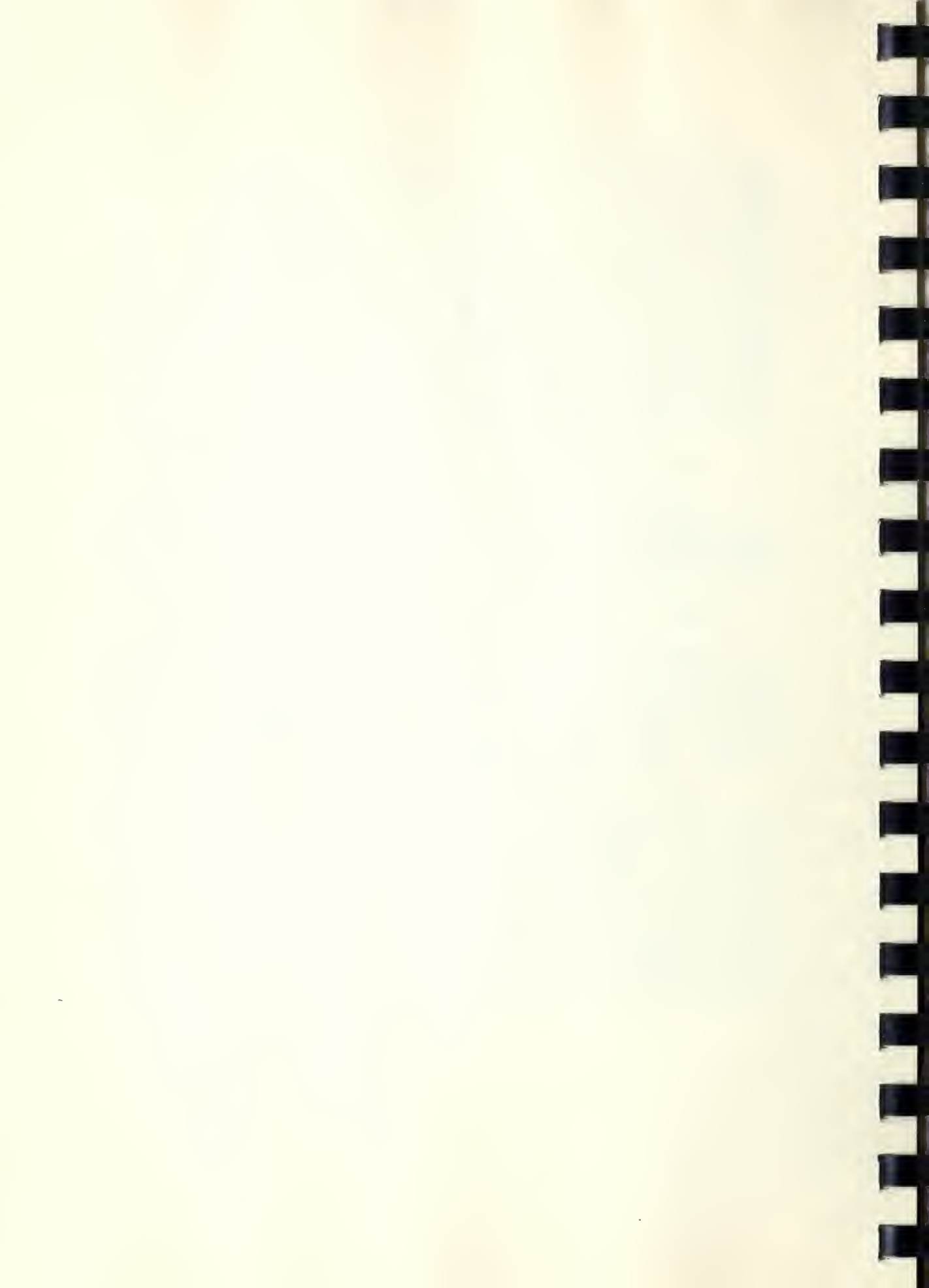
Figure 64

extruded, interlocking, channel-type, aluminum alloy with integral flashing. There were cross rails, or bows, for meat rails but no meat rails were provided. This was a two-axle trailer with the axle assembly designed for shifting forward or backward to adjust for loading and road conditions.

III. Fruehauf - Used, from Emery Transportation Company

The semi-trailer loaned to the National Bureau of Standards, for laboratory and road tests, by the Emery Transportation Company was built by the Fruehauf Trailer Company to Emery Transportation Company specifications, and it had been in commercial use before being delivered for tests. The Model Number was WSRRR5535SR, and the Serial Number 28314. The hub odometer mileage was about 60,000 miles. Fig. 25 is a view of this trailer.

This was a two-axle semi-trailer and the overall length was 35 feet, the width 8 feet, and the height approximately 12 feet. The outer skin was of riveted aluminum construction. The inside length was approximately 34 feet, the width 7 feet, 3 inches and the height above the drainage level of the floor 6 feet, 11 inches. The empty weight was 13,510 pounds.

According to specifications furnished by the Emery Transportation Company the floor of the trailer consisted of a 3/8-inch marine plywood subfloor, coated on both sides with a water emulsion type undercoating. Over the subfloor were 4 inches of expanded polystyrene with all joints sealed with the same type of emulsion, and over the insulation there was an aluminum-alloy interlocking channel type flooring. This flooring was supported on wood fillers over each frame cross member. The depth of the channel grooves in the flooring was 1 1/8 inches. The side walls contained a four-inch thickness of 3/4-pound glass fiber insulation with a paper vapor barrier in the center of the insulation thickness except the lower ten inches of the walls, which were insulated with expanded polystyrene. The inner wall surface of the trailer consisted of 5/16-inch plasticized plywood except for the aluminum flashing at the floor. The roof was insulated with six inches of 3/4-pound glass fiber insulation with a paper
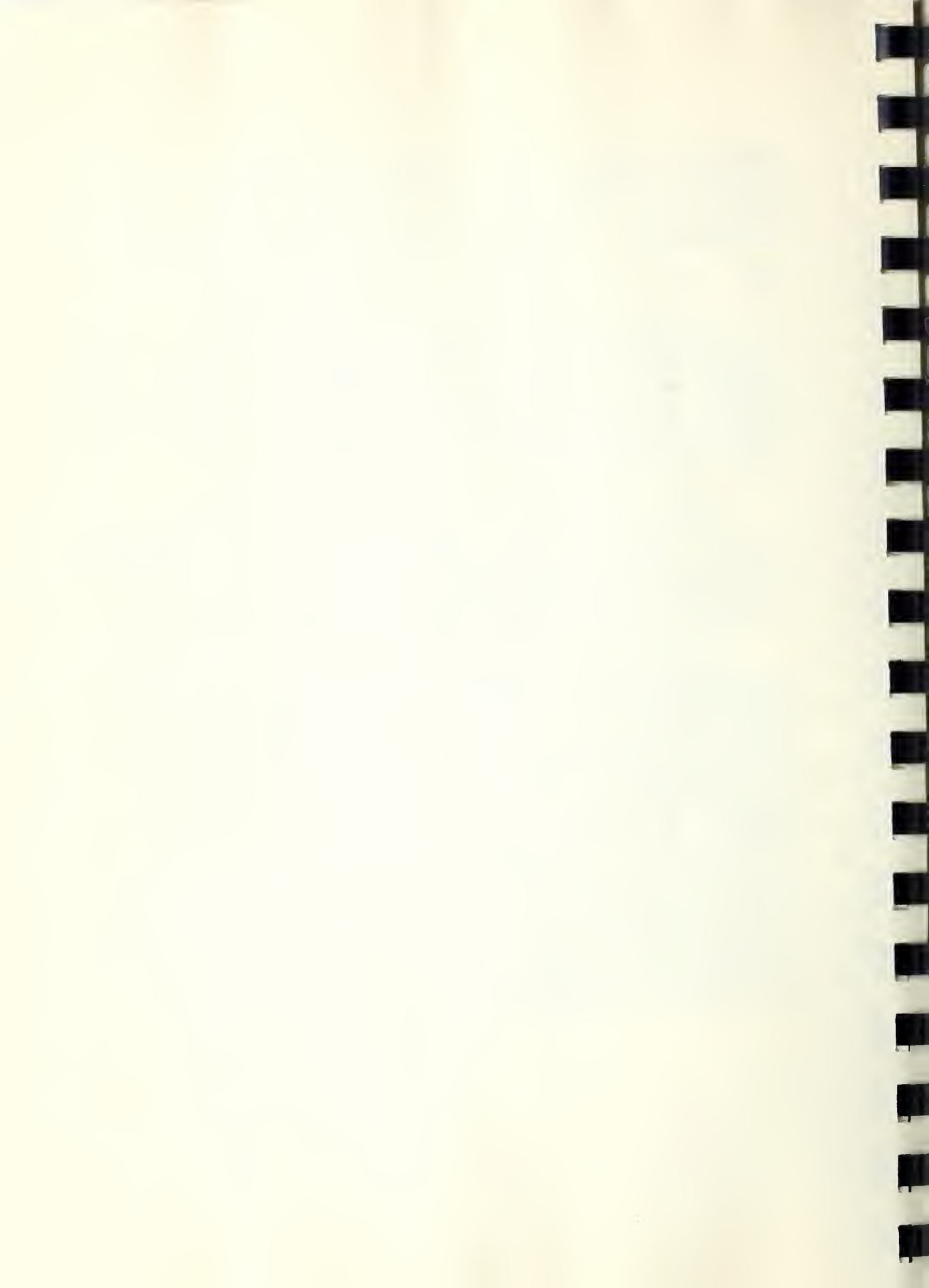
Figure 25

vapor barrier in the center of the insulation thickness, and
the ceiling surface was 5/16-inch plasticized plywood. The
construction of the rear door was the same as the side walls
except that the flashing on the lower portion of the door
was stainless steel. The trailer was equipped with seven
2-inch pipe meat rails, each supported by 13 hangers attached
to wooden cross beams. The three center rails were shorter
than the four outside rails leaving a 45-inch space at the
front end for the refrigeration unit.

4. Laboratory Test Procedures and Results

The laboratory tests of each trailer were made to deter-
mine the heat transfer rate and simultaneous gain in weight
due to accumulation of water or ice under specified laboratory
conditions for comparison with the heat transfer rates under
actual road operation.

Conditions of 100F dry bulb temperature and 50 percent
relative humidity were chosen for the ambient space around
the trailer with 0F temperature in the cargo space of the
trailer as typifying moderately severe operating conditions.
The weight gain during the test was measured with three plat-
form scales on which the trailer was supported. The heat
transfer rate was determined by use of the prototype heat
sink apparatus. Fig. 26 is a schematic diagram of the heat
sink apparatus. See Fig. 4 for schematic arrangement of the
refrigerant circuits.

The principle of operation of the heat sink is as
follows:

The temperature rise of the brine in the coil inside the
trailer under test and the temperature rise across a heater
in series with this coil are measured. (See Fig. 25.) The
heat input to the heater is measured. Since the brine flows
through the coil in the trailer and the heater chamber at the
same rate, the ratio of the temperature rise of the brine in
the coil to the temperature rise of the brine in the heater is
equal to the ratio of the amount of heat absorbed by the brine

COMPARISON TYPE HEAT SINK CALORIMETER
FOR REFRIGERATED TRAILERS

DEVELOPED BY NATIONAL BUREAU OF STANDARDS

SYMBOLS: ΔT1 TEMPERATURE DIFFERENCE OF BRINE ACROSS TRAILER
ΔT2 " " " " " " BRINE HEATER
ΔT3 " " BETWEEN AIR IN TRAILER
AND TEST ROOM
tc1, tc2, etc. TEMPERATURE MEASUREMENT POINTS
(H1), (H2) ELECTRIC HEATERS RATED IN BTU/HOUR

FIGURE 26

COMPARISON TYPE HEAT SINK CALORIMETER
FOR REFRIGERATED TRAILERS

DEVELOPED BY NATIONAL BUREAU OF STANDARDS

SYMBOLS: ΔT1   TEMPERATURE DIFFERENCE OF BRINE ACROSS TRAILER
           ΔT2   "   "   "   "   "   "   " BRINE HEATER
           ΔT3   "   "   "   BETWEEN AIR IN TRAILER
                                                    AND TEST ROOM
           tc1, tc2, etc. TEMPERATURE MEASUREMENT POINTS
           (H1),(H2) ELECTRIC HEATERS RATED IN BTU/HOUR
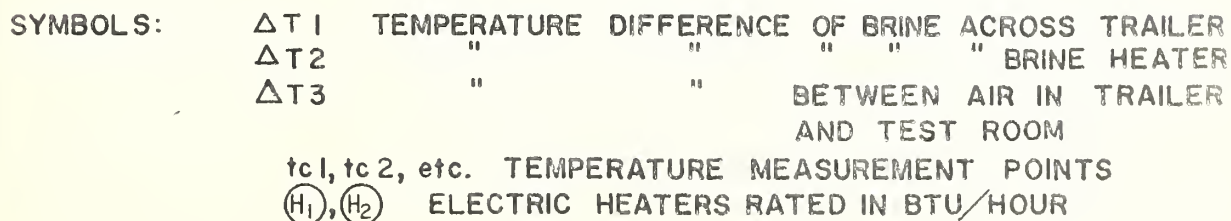
FIGURE 26

in the coil to the amount of heat absorbed by the brine in the heater. The equality of these two ratios would be as follows:

$$\frac{\Delta T_1}{\Delta T_2} = \frac{\text{Heat Gain of Trailer} + H_1}{H_2}$$

where H_1 is the sum of all of the items of auxiliary heat added to the trailer interior for purpose of test, such as fans, blower(s), controlling heat, etc.

H_2 = heat release in the heater in series with the brine coil.

ΔT_1 = temperature rise of the brine in the coil inside the trailer.

ΔT_2 = temperature rise of the brine from inlet to outlet of the series heater.

The heat gain of the trailer would then be:

$$\text{Heat Gain (Btu/hr)} = \left(\frac{\Delta T_1}{\Delta T_2} \times H_2 \right) - H_1$$

To determine the heat gain of the trailer per unit temperature difference between interior and exterior the total heat gain in Btu/hr can be divided by this temperature difference, ΔT_3.

$$\text{Heat Gain, Btu/hr(°F)} = \frac{\left(\frac{\Delta T_1}{\Delta T_2} \times H_2 \right) - H_1}{\Delta T_3}$$

The slight change in specific heat of the brine between the coil and the heater, and the slight heat leakage of the insulated brine heater, were found to be negligible for these determinations.

To measure the net heat leakage and weight gain of each test trailer, the following variables had to be controlled and/or measured:

      1.   Temperature (100F) and relative humidity (50%) of the ambient space around the trailer.

      2.   Temperature (0F) inside the trailer.

      3.   Temperatures at various points in the brine circuit:

          a.   inlet to coil in trailer
          b.   outlet from coil in trailer
          c.   difference across coil in trailer
          d.   inlet to series heater
          e.   outlet from series heater
          f.   difference across series heater.

      4.   Electric power introduced into trailer during test for fans, etc.

      5.   Weight of the trailer.

      6.   Time (relative).

All temperatures were measured with calibrated copper-constantan thermocouples. Temperature differences in the brine circuit were measured with five-junction thermopiles in wells to increase the accuracy of these readings. The ambient temperature was taken as the average of the air temperatures six inches from each of the eight corners of the test vehicle. The interior temperature was taken as the average of the air temperatures at 12 points, one each six inches from the adjacent surfaces in each of the eight interior corners, and four at similar positions at the center (midlength) of the trailer. In addition, other temperature measurements of exterior surfaces etc., were made for comparison with conditions observed during road tests.

All electric power used to operate fans, lights, and the heater which was used to obtain final temperature control in the trailer was measured by means of watthour meters.

The total weight gain of the trailer was determined by periodic observation of the three platform scales on which the test vehicle was supported. The portion of the weight gain due to accumulation of frost or ice on the cooling coil was determined by weighing the defrost water at the end of each test. The scales used to weigh the trailer were read to the nearest one-half pound and had previously been calibrated through the range of weights involved. Fig. 27 shows a trailer in position for test.

All readings were taken at regular time intervals for a sufficient period after steady state operation was attained to establish weight gain and heat transfer rates.

The measured cooling loads of three commercial trailers under laboratory conditions are shown in Fig. 28 (also in Table II) and the corresponding rates of weight gain are shown in Table I.

Table I

Weight Gain of Three Commercial Trailers
under Laboratory Conditions
(Ambient 100F, 50% R. H. Interior OF)

Trailer	Avg. Weight Gain Rate, lbs per hour
A	0.32
B	0.98
C	0.54

In Fig. 28 and in Table II trailers A, B, and C are shown to have total cooling loads of 10,300, 9520, and 7500 Btu/hour, respectively. The portion of the total heat gain due to air leakage effects was computed to be 740, 2270, and 1250 Btu/hour, respectively. For this computation, it was assumed that the weight gain was due entirely to accumulation of water or ice and that the water vapor entered the insulation and cargo space as a result of movement of the moist ambient air through the trailer exterior. It was further assumed
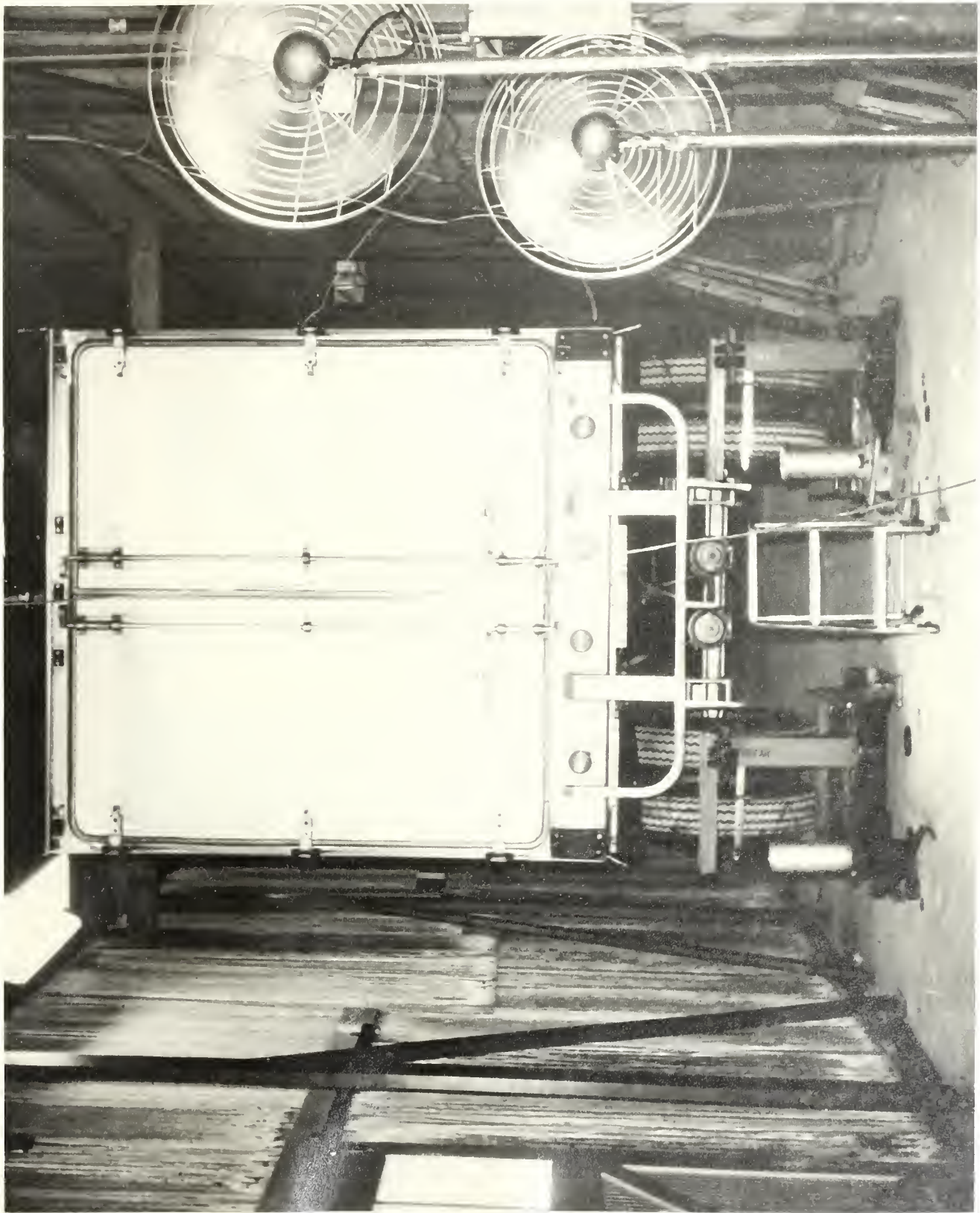
Figure 27

HEAT GAIN RATE OF THREE COMMERICAL TRAILERS UNDER LABORATORY CONDITIONS
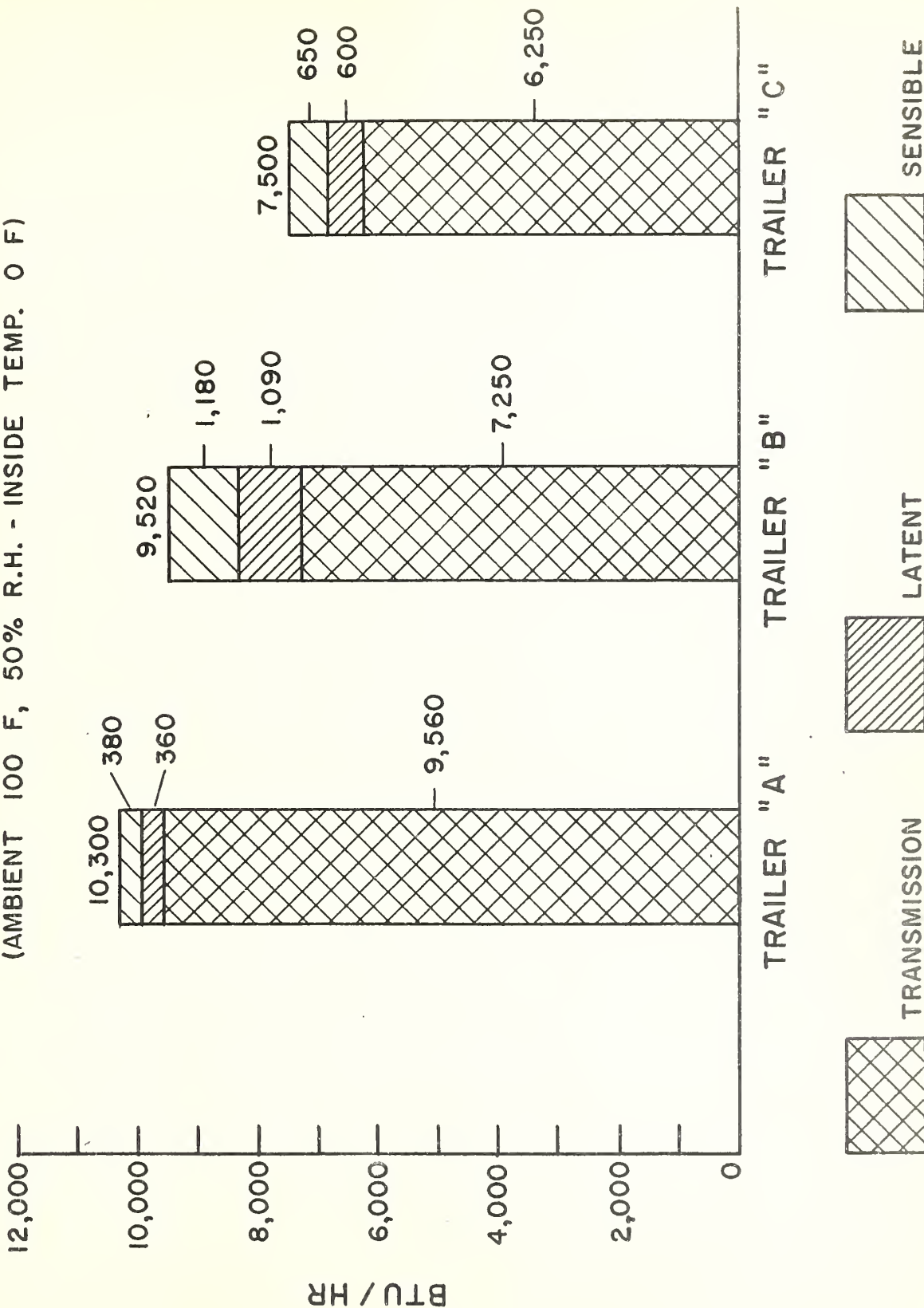
(AMBIENT 100 F, 50% R.H. - INSIDE TEMP. O F)

FIGURE 28

It is probable that the air leaving the trailer was not cooled to OF and possible that it was not saturated. In either event, the amount of water vapor surrendered per pound of air would have been less than was assumed and the corresponding air leakage would have been greater. For example, if the leakage air were assumed to leave the trailer saturated at 32°F instead of 0°F, the amount of moisture surrendered would be 119.5 grains per lb of air instead of 140.5 grains. In this case, the computed air leakage would have been 273, 837, and 461 cu ft of ambient air per hour and the sensible heat gain due to air leakage would have been 307, 939, and 517 Btu/hr for trailers A, B, and C respectively; the latent heat gain would remain essentially the same for either case since it is directly related to the average gain in weight of the trailer. It is probable that the leakage air actually left the trailer at a dew point somewhere between OF and 32F since most of the moisture was deposited as frost in the walls where the temperatures were above OF.

During the laboratory tests of each trailer, simultaneous measurements of air leakage into the cargo space were made using helium as a tracer gas. These results are presented in Section 7 on Air Infiltration.

5. Road Test Procedures and Results

The road tests of the three commercial trailers were made primarily to determine the heat transfer rates of each trailer while being operated at a road speed of 50 miles per hour for comparison with the laboratory results when the vehicles were stationary. The trailers were empty except for test equipment. As outlined in Section 2, provisions were made for observing a number of variables, such as skin temperatures, static and impact air pressures on various parts of the trailer, relative solar radiation incidence, temperature and relative humidity of the ambient air, road speeds, brine flow, etc. It will be noted in comparing Fig. 10 (refrigerant circuits for the mobile equipment) with Fig. 4 (refrigerant circuits for the laboratory tests) that two variations of the heat sink method were used for the road and laboratory tests. The refrigerating effect at the coil in

the trailer for the road tests was determined by means of a flowmeter in the brine circuit and the temperature difference of the brine entering and leaving the coil, whereas in the laboratory tests the heat gain in the trailer was determined by comparing the temperature rises produced in the same brine circuit across a measured electrical source and the cooling coil in the trailer. This modification was employed to reduce the electric power and refrigerating capacity demand for the road tests. The heat gain rate per unit temperature difference across the walls for the trailer during each test run was computed using the following equation:

$$\text{Heat Gain Rate, Btu/hour } (°F) = \frac{(M \times Cp \times \Delta T_1) - H_1}{\Delta T_2}$$

where M = flow of methylene chloride brine, pounds per hour

   Cp = specific heat of brine, Btu per pound ($°F$)

   ΔT_1 = temperature rise of brine through coil in trailer, $°F$

   ΔT_2 = average temperature difference between air in trailer and ambient air, $°F$

   H_1 = heat equivalent of electric power in trailer for fans and heater, Btu per hour

All road tests were made on the Ohio Turnpike during September and October, 1957. This location was selected because it was the nearest to Washington, D. C., which most nearly suited the conditions necessary for continuous operation at 50 miles per hour. The tests were conducted from Milan, Ohio, which is located at about the center of the Turnpike. Fig. 29 shows one of the test trailers at the Milan entrance to the Turnpike.

Figure 29

A typical test run was of approximately 5 hours and 30 minutes duration for each driver and observer team including turn-around and refueling. The distance traveled was 119 miles each way from Milan to the western terminus of the Turnpike and return, a total of 238 miles, and the 50 mile per hour road speed was maintained except for the time required to turn around at the far end of the run and to refuel at Milan. The time interval between runs was determined by the time required to change drivers, refuel and check oil, brakes, lights, etc. for the tractor-trailer and the three gas engines used to drive the generator and refrigerating unit. A retail gasoline station, used as a change point was located less than 1/4 mile from the Milan entrance to the Turnpike and, usually, the time off the highway for refueling did not exceed 20 minutes. On the basis of 10 minutes for the turn-around and a total of 30 minutes for leaving and reentering the highway, and refueling, about 87 percent of the elapsed time for each test run of 238 miles represented operation at 50 miles per hour. For a majority of the tests, the drivers were able to control the speed to within ±2 miles per hour during the 50-mile-per-hour portions of the run. As far as possible the test runs were continuous and deviated from this schedule only when repairs or maintenance were required between runs.

About 72 gallons of fuel (regular grade gasoline) were required for a typical test run for the tractor and the three other engines driving the generator and refrigerating unit, an average of 13.1 gallons per hour for the total run.

All test runs were made with the trailer interior temperature controlled as near as possible to OF, regardless of variation in ambient temperature, relative humidity and incident radiation.

During the test runs the observer read and recorded measurements of all variables at 30-minute intervals, and a complete set of readings required about 20 minutes. The tractor-trailer combination was weighed at the beginning and end of the road tests of each trailer. The total mileage involved in the road tests of the three vehicles was about 15,000.

An attempt was made to measure the air infiltration of one of the test trailers using a modified form of the helium tracer-gas technique, but the results were not considered dependable because of possible malfunctioning of the sensing instrument.

In general, the heat transfer values reported are the average for not less than 24 hours of continuous test operation for a period when the initial and final ambient temperatures and incident solar radiation were not far different. It must be understood that ambient temperature and humidity and solar radiation varied from one test run to another, so that "steady-state" operation was not attained, even though the interior temperature was held essentially constant.

Fig. 30 shows the heat gain rate of the three test vehicles. Because the ambient conditions were not identical, the heat transfer rates, to be comparable, are expressed in Btu per hour per degree F air temperature difference between interior and exterior of the trailer. From Fig. 30 it can be seen that trailers A, B and C had heat gain rates of about 117, 113 and 88 Btu per hour (°F) respectively.

Figs. 31 and 32 show the corresponding ambient humidities and heat gain rates for the several test runs on trailers A and C. In Fig. 31 the ambient absolute humidity was of the same order of magnitude for all test runs and there was no trend toward a rising or falling heat gain rate for the series of runs.

In Fig. 32 the ambient absolute humidity decreased significantly during the 19 test runs, and the measured heat gain rate also showed a significant corresponding decrease.

Fig. 33 shows the heat gain rates of the three test trailers extrapolated from the comparative results of the laboratory and road tests for assumed operating conditions of 100F ambient temperature at 50 percent relative humidity, an interior temperature of 0F, and a road speed of 50 miles per hour.

HEAT GAIN RATE OF THREE COMMERICAL TRAILERS
DURING ROAD TESTS *

(SPEED 50 M.P.H. AND PREVAILING AMBIENT CONDITIONS)

* AVERAGE OF TEST RUNS

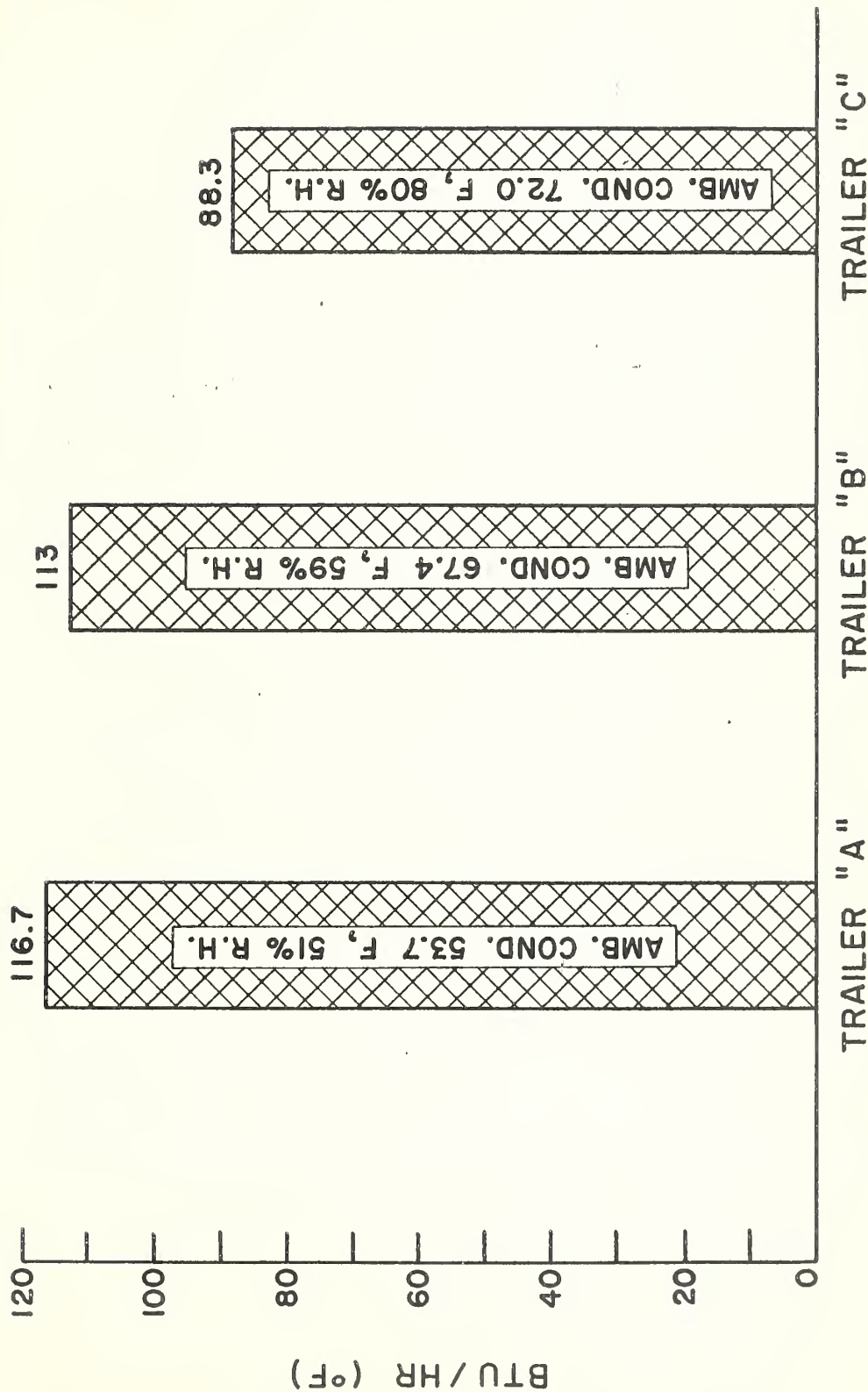FIGURE 30

AMBIENT HUMIDITY VS. HEAT GAIN RATE
DURING ROAD TESTS
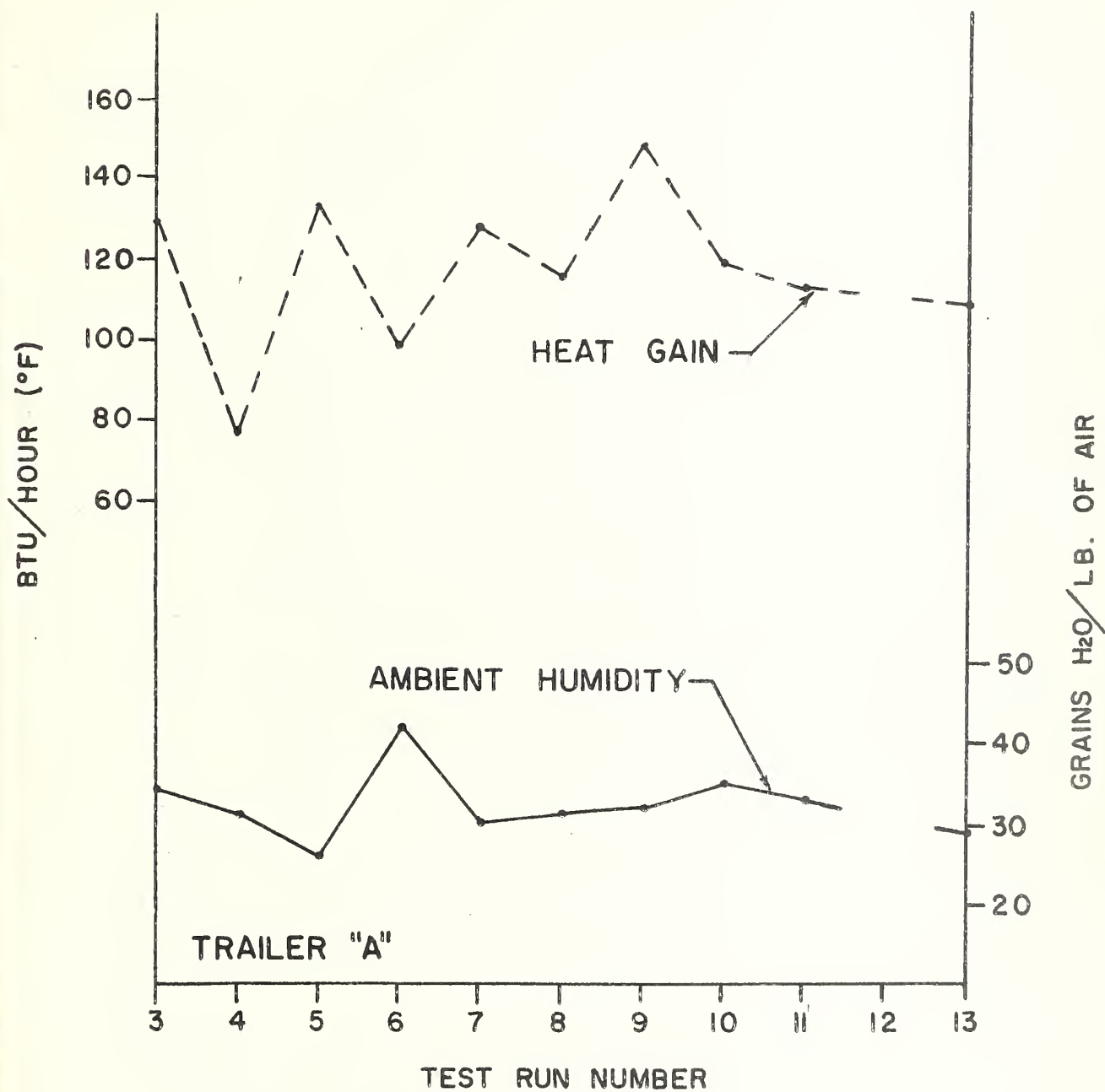
FIGURE 31

AMBIENT HUMIDITY VS. HEAT GAIN RATE DURING ROAD TESTS

HEAT GAIN

AMBIENT HUMIDITY

TRAILER "C"

TEST RUN NUMBER
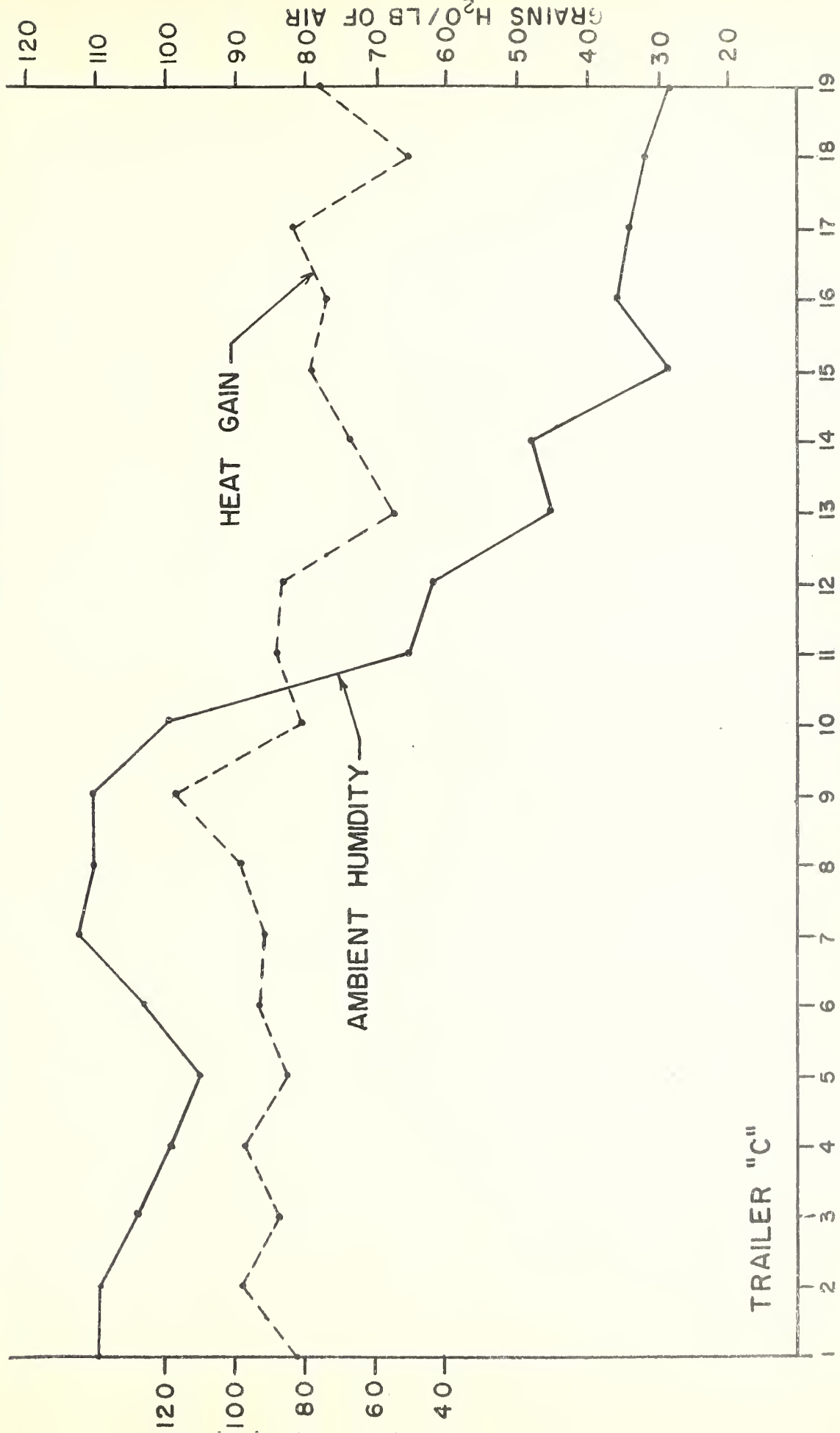
GRAINS H_2O/LB OF AIR

FIGURE 32

EXTRAPOLATED HEAT GAIN RATE OF THREE COMMERCIAL TRAILERS
(AMBIENT 100 F, 50% R.H., INSIDE TEMP. O F, AND 50 M.P.H.) *
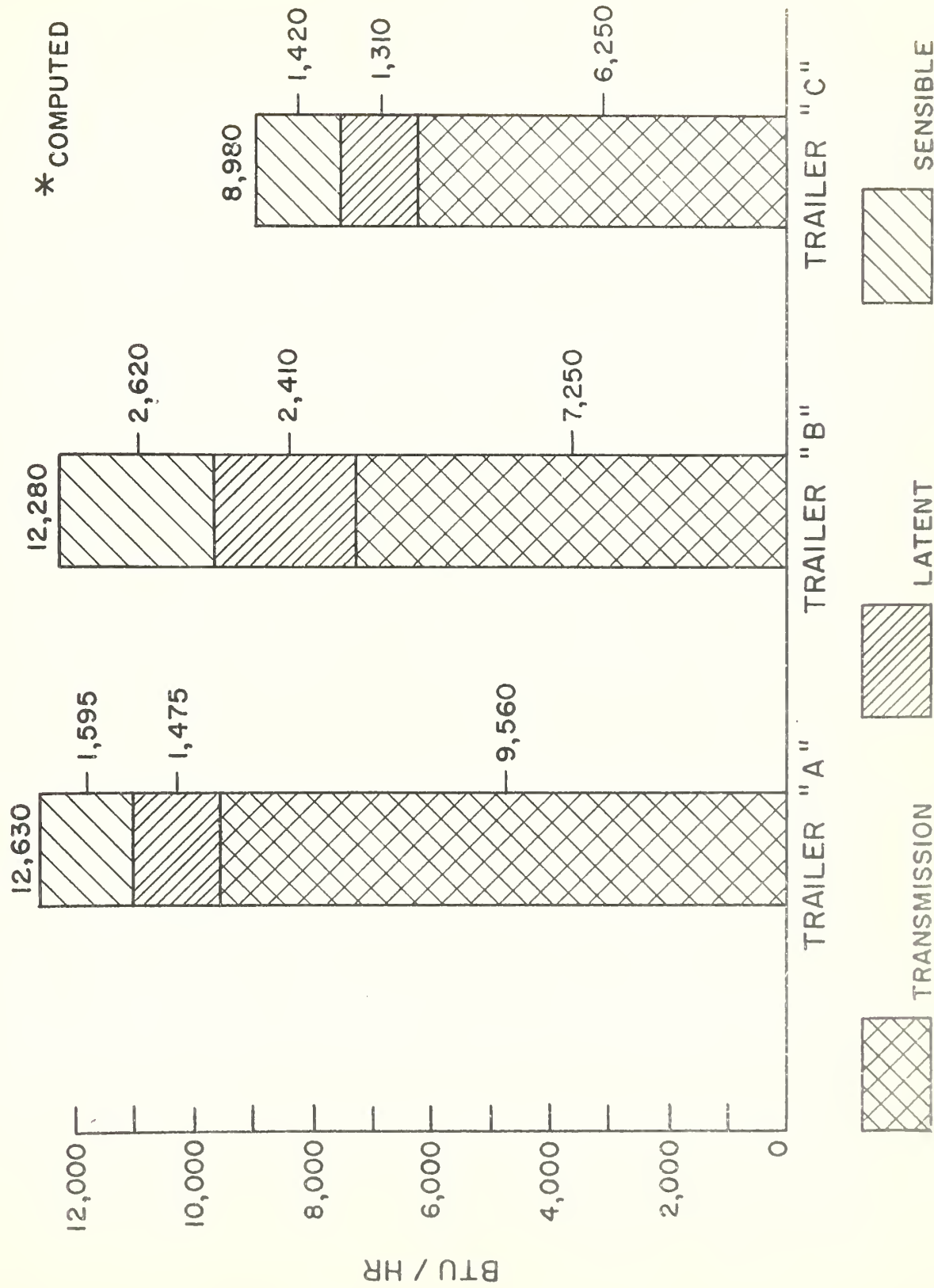
* COMPUTED

FIGURE 33

The extrapolated values were obtained by the following steps:

      1. The heat transmission rate (exclusive of air leakage) was assumed to be the same for road operation as for laboratory operation at the same temperature difference, and was so determined for the temperature difference observed during the road tests.

      2. The remainder of the heat gain rate observed on the road was assumed to be caused by air leakage at 50 mph road speed.

      3. The air leakage rates required under the ambient conditions observed on the road to cause the increment of heat gain in excess of heat transmission (item 2 above) were computed assuming that the leakage air left the trailer saturated at OF. The air leakage rates thus determined for trailers A, B, and C were 66.5, 109.3, and 59.1 pounds per hour, respectively, corresponding to about 970, 1590, and 860 cu ft/hr at conditions of 100F and 50 percent R. H.

      4. The heat gain rate due to air leakage at ambient conditions of 100F and 50 percent R. H. and 50 mph road speed was computed on the assumption that the leakage rate at a given road speed was independent of ambient temperature and humidity.

      5. This heat gain rate due to air leakage was added to the transmission heat gain rate determined in the laboratory for 100 degrees temperature difference between inside and outside the trailer to determine the total anticipated heat gain rate under road operation at 50 mph in ambient conditions of 100F and 50 percent R. H.

It is recognized that the transmission heat gain for a given air temperature difference was probably greater during the road tests because of solar radiation, heating of the under surface of the floor, and an improved heat transfer coefficient on all surfaces due to higher air velocity, but computation shows that these effects are small as compared to the increase due to air leakage.

The extrapolated heat gain rates, as shown in Fig. 32, are 12,630, 12,280, and 8980 Btu per hour for trailers A, B and C respectively.

All of the test vehicles gained weight during the series of week-long test runs, the increase ranging from 130 to 230 lbs. Since operating and ambient conditions varied considerably for the three trailers and because the precision of the weighing process is uncertain, no direct relation of rates of moisture gain can be established from the weight values, other than to confirm that a significant weight gain, due primarily to accumulation of ice and/or water, does occur. For two of the test trailers which were refrigerated below 20F for the entire period between initial and final weighing in Washington, D. C., an average time of eight days, the coil in the trailer was not defrosted until after the final weighing and the amount of ice on the coil did not exceed 15 pounds in either case. The doors on these two trailers were not opened between weighings.

Although the tests were not intended to include detailed studies of skin temperatures, the temperature at one point each on the exterior surface of the two sides, top and bottom, was observed. Fig. 34 shows observations made during one of the return trips from the Ohio Turnpike when it was convenient to stop just before noon (Eastern Standard Time) with a clear sky and bright sun. Although the sky clouded over somewhat between noon and 2:00 P. M., certain comparisons can be made from Fig. 34. The right hand scale shows relative incident radiation measured with a pyrheliometer, and is expressed in microvolts. Bright sunlight gave a reading of nearly 3000 microvolts, no sunlight gave a reading near zero. Note the decrease in the temperature of the top and right side surfaces and the simultaneous increase in the temperature of the bottom surface when travel at 50 miles per hour commenced about 10:35 and the reverse when the vehicle was stationary during the times before and after this period. The observations during the period when the vehicle was again in motion after 1:10 P. M. are not as conclusive because of intermittent clouds and change of speed between 20 and 50 miles per hour, including the two stops involved in leaving the Ohio Turnpike and

EFFECT OF MOTION ON SKIN TEMPERATURES

FIGURE 34

entering the Pennsylvania Turnpike between 2:30 and 2:40 P. M.
While Fig. 34 shows data from only one of the test vehicles,
it was noted that all of the vehicles showed similar
characteristics. The bottom surface temperature was from 5
to 15 degrees F warmer than the ambient air temperature
whenever the vehicle was in motion, day or night, in rainy
or dry weather. These skin effects will be discussed further
in Section 6.

During the road tests, the velocity pressure of the air
above and slightly ahead of the leading edge of the tractor
was measured with a Pitot tube. In addition, the differences
between the static pressure at the Pitot tube and (1) the
static pressure in the trailer interior and (2) the static
pressure in the trailer wall were measured. The velocity
pressure of standard air (70F and dry at 29.92 in. Hg) moving
at 50 miles per hour (4400 feet per minute) is very nearly
1.21 inches of water pressure. During the test runs at 50
miles per hour, velocity pressures observed ranged from
0.6 in. W.G. to 2.0 in. W.G. depending primarily on the
velocity and direction of the wind. At the time that the
2.0 in. W.G. velocity pressure was observed, the driver
reported that, at full throttle on level ground, he could
maintain only 49 miles per hour. On the return leg of that
same trip, the driver stated that only light throttle was
required to maintain 50 miles per hour and the observed
velocity pressure was much lower. In all cases where wind
direction or gusts did not seriously affect the performance
of the Pitot tube, observed velocity pressures at 50 miles
per hour were from 1.1 to 1.25 in. W.G.

The observed difference between the static pressure at
the Pitot tube and the static pressure in the cargo space of
the vehicle ranged from 0.2 to 0.4 in. W.G. with lower
pressure in the cargo space for all of the test vehicles at
50 miles per hour. The difference observed between the static
pressure at the Pitot tube and the static pressure at one
point in the trailer wall was essentially the same as that
for the trailer cargo space.

6. Comparison of Laboratory and Road Test Results

    As described in Sections 1 and 2, two variations of the
heat sink method were used to measure the total heat gain of
the test trailers during laboratory and road tests. A test
was made to determine the agreement between these different
and completely independent measuring systems, (1) the stationary
laboratory equipment using the comparison principle, and
(2) the mobile equipment using the flowmeter principle. This
was accomplished by comparing the observed heat gain rate
measured with the laboratory equipment with the observed heat
gain rate measured with the mobile equipment with the same
trailer exposed to identical conditions, (Ambient 100F, 50%
R. H., Interior Temp. OF) in the laboratory in each case. To
test the trailer in the laboratory with the mobile equipment
the trailer was placed in the test chamber with the front end
near the overhead sliding doors. The tractor was uncoupled
and moved forward as far as the electrical and refrigeration
lines would permit, and the overhead doors lowered as far as
possible. The open spaces below and around the door were
closed off so that the desired ambient conditions could be
maintained in the test chamber. By placing the tractor out-
side the test area, the heat produced by the gasoline engines
of the electric generator and of the two refrigeration machines
could be dissipated to the outside atmosphere without affecting
the conditions in the test chamber.

    All test data recorded were taken from measurements and
observations made with the road test instruments in the tractor
cab. All of the electrical current and refrigeration required
for the test was produced by the equipment mounted on the
tractor, just as had been done during the road tests. Only
the temperature and humidity conditions of the test chamber
were controlled by laboratory equipment.

    The test room ambient temperature and relative humidity
were controlled at 100F and 50 percent, respectively. The
trailer interior temperature was controlled at OF.

The heat transfer rate of the trailer as determined by this test agreed with the rate determined by the laboratory test, described in Section 4, within one percent.

This agreement, which is less than the expected testing error, indicated that the two measuring systems, laboratory and mobile, were suitable for comparison of laboratory and road results.

From Section 4, the observed heat gain rates of three trailers were 10,300, 9,520 and 7,500 Btu per hour at laboratory conditions of 100F ambient temperature at 50 percent relative humidity and a trailer temperature of 0F.

From Section 5, the observed heat gain rate and average ambient humidity for each trailer during the road tests was as shown in Table III, and the trailer temperature was at or near 0F in each case.

Table III

Observed Heat Gain Rates of Three Commercial
Trailers in Laboratory and Road Tests

Trailer	Laboratory (Amb. 100F, 50% R.H. Interior 0F)		Road (Trailer Interior Temp. 0F)		
	Btu/hr	Btu/hr(°F)	Avg.Conditions	Btu/hr	Btu/hr(°F)
A	10,300	103.0	53.7F,51% R.H.	6,260	116.7
B	9,520	95.2	67.4F,59% R.H.	7,610	113.0
C	7,500	75.0	72.0F,80% R.H.	6,360	88.3

The different conditions of ambient humidity and temperature during the road tests, as well as changing solar radiation, etc., undoubtedly affected somewhat the absolute value of the coefficients determined by dividing the observed heat gain rates by the difference in temperature inside and outside of the test vehicles. The coefficient so determined, however, is perhaps the most suitable way to compare the overall performance of vehicles when ambient conditions vary between

tests, and from Table III it can be seen that the increases
in heat transfer coefficient during road tests for trailers A,
B and C were, respectively, 13.3 percent, 17.6 percent and
17.7 percent as compared to the laboratory results. The
increase in heat gain of a trailer during road operation is
due primarily to greater air leakage when the vehicle is
moving, but some of the increase is the results of (1) solar
radiation and (2) heating of the under surface of the vehicle
due mainly to waste heat from the tractor engine and partly
from radiation off the road surface, and (3) an improved heat
transfer coefficient at all exterior surfaces because of
higher air velocity. Other than the effect of air leakage,
the increase in heat gain rate due to the several skin effects
will probably not account for more than five or six percent
increase for a 24-hour period with bright sunlight during the
day. Fig. 34 in Section 5, a graph of the effect of motion
on skin temperatures for one of the test vehicles, shows that
when the trailer is in motion, the under side of the vehicle
is the greatest source of increased heat transfer due to skin
effects, and, in the case of these tests, was affected by
location of the engine exhaust ~~under~~ the tractor rear axle
and the waste heat from the generator and refrigerating unit
engines.   *Tractor,*

.   When a trailer is stationary in bright sunlight, Fig. 34
shows that the top and one side can be heated by solar
radiation at least 25 degrees F higher than the ambient air
temperature. The top and one side of a typical 35-foot
trailer is about 45 percent of the total surface. The effect
of increasing the temperature of these surfaces 25 degrees is
equivalent to increasing the ambient temperature around the
entire vehicle by about 12 degrees or 12 percent at conditions
of 100F ambient temperature and OF trailer temperature. This
is offset some by the decrease in the temperature of the under
surface when the vehicle is stationary, and it must be
remembered that heavy solar loading will not exist more than
about six hours per day.

     In Section 5, the method used to extrapolate the heat gain
rates of the three test vehicles at conditions of 100F ambient

temperature, 50 percent relative humidity, OF trailer tempera-
ture and a road speed of 50 miles per hour was outlined and
the extrapolated values are shown in Fig. 33. Fig. 35 is a
comparison of the observed laboratory and extrapolated road
heat gain rates at these conditions, and is based on the
assumption that air leaving the trailer is at OF and saturated.
From Fig. 35 it can be seen that the expected increase in
heat rates between similar laboratory and road conditions is
22.5, 29.0 and 19.7 percent for trailers A, B and C, respec-
tively.

7. Air Infiltration

Air infiltration or air leakage is a major cause of
increased heat gain into refrigerated trailers, as the data
in Sections 4, 5 and 6 indicate.

In tests prior to the start of the work with the com-
mercial trailers, one of the military trailers (C) accumulated
about 850 lbs of ice in the insulated space when refrigerated
to an interior temperature of OF for 75 days under laboratory
conditions of 110F ambient temperature and 60 percent relative
humidity. This significant accumulation led to an investigation
of the mechanism of moisture transfer into the trailer con-
struction. Computation indicated that a negligible amount of
the total moisture could have entered the insulated space by
diffusion so it was concluded that air leakage served as the
mechanism for bringing in the moisture. Several approaches
were made to the problem using two military and three commercial
vehicles as test specimens. These investigations were com-
prised of the following main subdivisions:

1. Construction of an air infiltration meter using
the tracer gas principle.

2. Air leakage measurements into the cargo space of
four trailers, two military and two commercial, under stationary
conditions using the air infiltration meter.

3. Effect of sealing the door and refrigerating unit
plug on air leakage under stationary conditions.

COMPARISON OF OBSERVED LABORATORY AND EXTRAPOLATED ROAD HEAT GAIN RATES OF THREE COMMERCIAL TRAILERS (AMBIENT 100 F, 50% R.H. - INSIDE TEMP. O F, ROAD SPEED 50 M.P.H.)
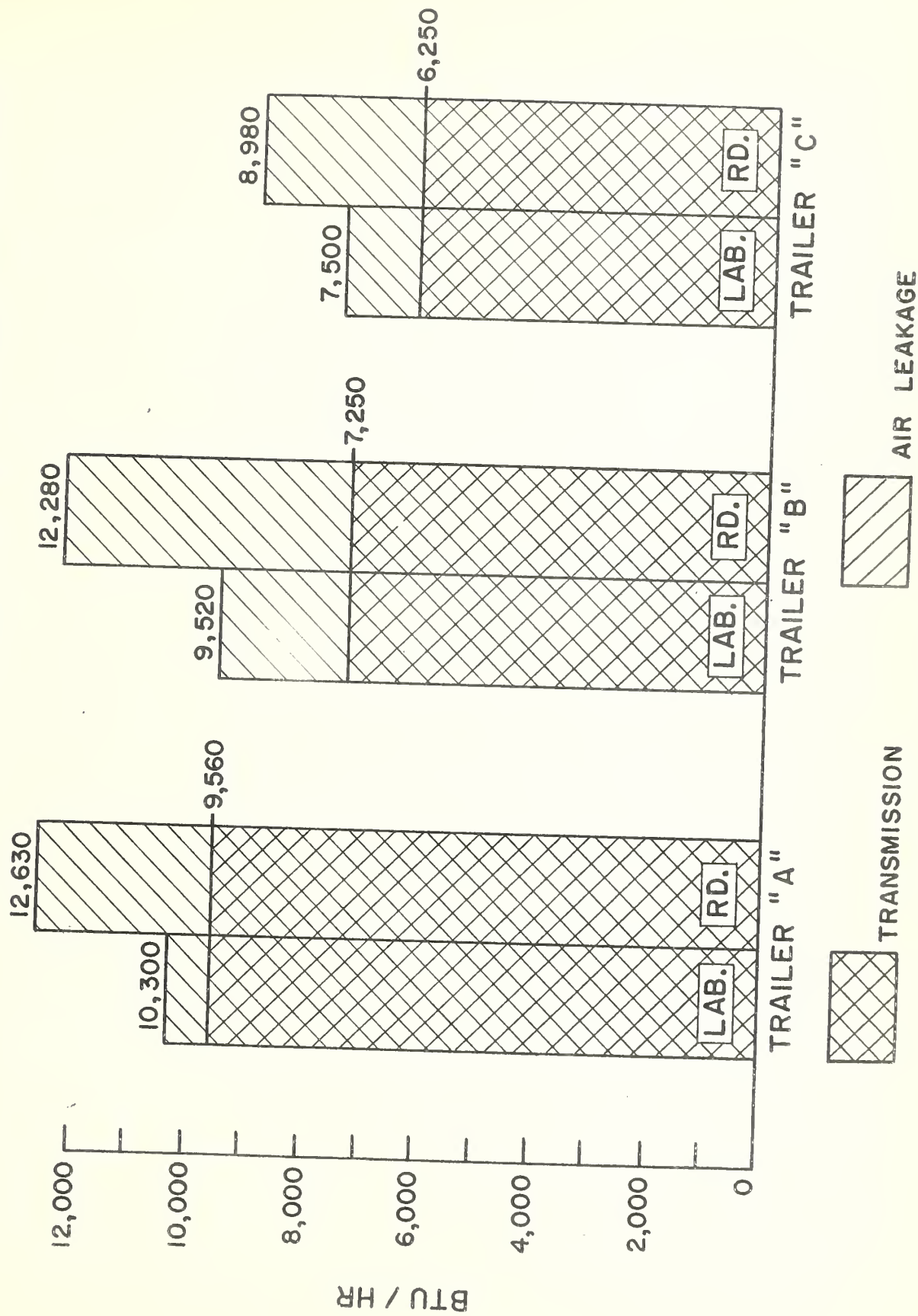
FIGURE 35

4. Computation of air leakage required to deposit the observed quantities of ice in the insulation.

5. Study of air flow patterns inside the insulated space.

6. Relation of forced ventilation air flow and pressure difference between inside and outside of a trailer.

7. Air pressure pattern on the exterior and interior skins of a trailer moving at 50 mph.

Based on the experience obtained in the design of an infiltration meter for buildings, an apparatus for measuring the air leakage of refrigerated trailers was designed and constructed. This new instrument is practical for use in both laboratory and road tests.

The sensing element is an aluminum cylinder 3 1/2 in. long and 1 3/4 in. in diameter with two cavities in each of which a thermistor is installed. One cavity is hermetically sealed and the other one is ventilated with the ambient air through two small holes at the top and two small holes at the bottom of the cavity. This sensing element, or probe, is installed in the trailer and connected by means of a three-conductor cable to the instrument in the tractor. This instrument contains the fixed and balancing resistors which form a Wheatstone bridge circuit with the two thermistors. It also contains an 18-volt dry-cell battery for the bridge power supply. The bridge current, as well as the voltage across the bridge, can be measured with a microammeter without altering their values during the test. This was possible by using high series resistances with the microammeter and a DPDT switch to change over from voltage to current readings. The bridge is balanced with a galvanometer. Another DPDT switch disconnects the leads of the galvanometer from the balancing circuit and connects the leads of a recording potentiometer or a recorder in their place to determine the unbalance of the bridge during the test. A shunt and a series resistor are provided to compensate for the amplification of the different electronic meters.

When the thermistor bridge circuit is balanced, helium, in the amount of approximately one half of one percent of the volume of the trailer, is introduced and mixed with the air in the trailer by the cooling unit blower. The thermal conductivity of helium is about six times as high as that of air and the helium-contaminated air causes a slight cooling of the thermistor in the ventilated cavity of the probe. This cooling in turn increases the resistance of this thermistor, which can be observed as an unbalance of the Wheatstone bridge circuit. The unbalance was found to be linearly proportional to the concentration of helium tracer gas. As air leaks into the trailer and an equal amount leaks out, the helium concentration will decay. By basic mathematic computation, it can be shown that the following relation exists between the concentration of the tracer gas and the air changes if the possibility of a build up in helium concentration in the insulation space is neglected.

$$A = \ln \frac{c_1}{c_2}$$

where   A = air changes during the time interval 1 - 2

ln = natural logarithm

c_1 = tracer gas concentration at time 1

c_2 = tracer gas concentration at time 2

As only the knowledge of the ratios of the tracer gas concentrations is required for determining the air change, the absolute tracer gas concentrations need not be determined.

The EMF values of the observed temperatures on the recorder or indicating potentiometer are determined for about one hour or longer in five- to ten-minute intervals and the natural logarithm of the ratio of each two EMF values gives the air change of the trailer for that time interval. In order to compensate for errors in individual readings and fluctuations in the infiltration due to wind or other effects, the average hourly infiltration rate is then determined as the arithmetical mean. The air leakage then is the product of the infiltration rate and the inside trailer volume:

$$L = V \times A$$

where   L = air leakage, CFH

V = trailer cargo space volume, cu ft

A = air changes per hour

The following table shows the air leakage values from the cargo space observed of four trailers in the laboratory.

Table IV

Trailer	Cargo Space Volume, cu ft	Temp. Gradient, °F	Cargo Space Air Changes hr^{-1}	Cargo Space Air Exchange, CFH
Military (a)*	677	89	0.075	51
Military (b)	750	109	0.28	211
Comm'l. (A)	∼1700	100	0.049	83
Comm'l. (C)	∼1700	100	0.036	61

*Observation made during reverse heat flow conditions.

The infiltration rates shown in the above table were determined by feeding helium gas into the interior of the trailer at a steady rate until the concentration therein became constant. This procedure tends to eliminate the error that is introduced if there is a two-way exchange of air between the insulation space and the interior of the trailer.

A comparison of Table IV with computed values of air leakage in Table II (Section 4) which are based on the observed rate of ice accumulation indicates that a greater amount of air is exchanged between the ambient and insulation space than between the ambient and cargo space. Further study of this relationship is needed to be certain of the air exchange pattern.

Initial observations of the helium trace apparatus indi-
cate that further development is needed to improve the accuracy
when the probe is exposed to low temperatures.

Because the air leakage of the military trailer (b) in
Table IV was relatively high, a second test was made with the
door and the joint around the panel of the cooling unit doubly
sealed. The latter was caulked with a mastic, the door was
sealed with masking tape, and another air leakage test under
otherwise similar conditions was made. This second test
indicated a decrease of the specific air leakage by about one
percent when the door and refrigerator plug were sealed, which
shows hat the leakage caused by these unsealed joints had
not appreciably affected the values observed during the first
test.

A few measurements were made to study the air flow pattern
inside the insulated space of the military trailer (b) by the
tracer gas method.

Gas samples were taken alternately from (1) the inside of
the trailer, (2) near the inside wall of the insulated space
and (3) near the outside wall of the insulated space adjacent
to (2). The inside temperature of the trailer averaged 5F and
the outside temperature averaged 112F. By introducing 0.61
cu ft/hr of helium steadily into the trailer, a concentration
of approximately 0.3 percent was maintained at steady state
conditions. In order not to disturb the air flow pattern in
the insulated space significantly the air samples were taken
at a rate of 0.6 ml/min (0.0013 cu ft/hr) and were drawn
through an infiltration probe until a steady state was reached.
Several samples were taken from each of the three stations.
The averages of the helium concentrations determined for each
station were:

1. Inside trailer 0.297 percent
2. Near inside wall 0.180 percent
3. Near outside wall 0.275 percent.

These data show that more of the fresh air from the space
surrounding the trailer moved through the insulation in a ver-
tical wall near the inside skin than near the outside skin.

Natural convection forces would cause the fresh air to enter leaks near the top of the trailer and leave through openings near the floor. At the same time, if there was natural convection within the insulated space, air would move downward near the inside skin, which is colder, and upward near the warmer outside skin. Thus the warm and humid fresh air would be drawn toward the inside skin and deposit its moisture on the colder surface. The frost pattern observed in the military trailer (c) and the helium concentrations cited above both corroborate this pattern of air movement.

Other tests were made in which the military trailer (b) was both pressurized and exhausted by means of a blower. Three different air flow rates were used and the inside pressure was compared with the outside pressure. The pressure gradient across the inside skin was also determined by installing a tube through the outside skin and insulating material terminating close to the inside skin. Table V shows the pressure differences observed.

Table V

Effect of Pressurizing and Exhausting of
Military Trailer (b)

	Air Flow Rate, CFM		
Pressurized	17	25	35
Inside to outside pressure, in. W.G.	0.037	0.065	0.101
Pressure across inside skin, in. W.G.	0.024	0.040	0.060
Exhausted			
Inside to outside pressure, in. W.G.	0.038	0.067	0.108
Pressure across inside skin, in. W.G.	0.026	0.041	0.068

This table shows that the pressure gradients were slightly higher when the trailer was exhausted than when it was pressurized at the same air flow rate. Several of these tests were repeated after the door and the refrigerator plug were sealed. The pressure gradients, then observed, did not differ

from the ones shown in Table V, which substantiates the pre-
vious finding that the leakage of the trailer was not caused
by the door or refrigerator plug seals.

To study the possible effects of air pressure set/up as
a result of motion, military trailer (c) was used to determine
the pressure patterns around a moving trailer. A Pitot tube
was mounted in front of a military M-52 tractor and 44 small
holes at selected places on the outside and inside skin of the
trailer were connected to a manifold so that the pressure at
each could be compared with the inside pressure of the trailer
and also with the ambient outside pressure as represented by
the static line of the Pitot tube. Stations for pressure
observation were established as follows:

        1 on the inside of the trailer
        2 on the nose
        6 on the one side
        2 on the rear
        2 on the second side
        7 on the roof
        2 on the floor

Except for the station inside the trailer, openings were pro-
vided at each station which permitted measuring the total
pressures on the exterior skin of the trailer and in the insu-
lation space. Pressures were measured at each station while te
the trailer was pulled down the highway at a nearly-constant
road speed of 50 mph. The following conclusions were derived
from the data:

        a. The pressure on the nose of the trailer was
closely related to the impact pressure in the Pitot tube
except where the front of the trailer was shielded by the
tractor. This pressure approximated 1 in. W.G. at 50 mph.

        b. The interior trailer pressure was approximately
1/4 in. W.G. lower than the static pressure at the Pitot tube
in front of the tractor.

c. The insulation space acted essentially as a constant-pressure plenum, ranging from 0 to .06 in. W.G. below interior trailer pressure.

d. The pressure difference between exterior skin and insulation space was such as to drive air into the insulation space on the nose and rear of the trailer and on the rear five stations on the roof. At the other stations on the sides, floor, and roof the exterior skin pressure ranged from .07 in. W.G. below to .05 in. W.G. above that in the insulation space. The pressure difference at some of these latter groups of stations fluctuated from positive to negative during the test.

These preliminary investigations of air pressure distribution and exchange patterns within an insulated trailer showed the need for further work in these areas. Improvement of the helium trace apparatus and additional laboratory tests of the commercial trailers are currently in progress.

If a trailer did not leak air into the insulated space or cargo space, there would be but little increase in heat gain at 50 miles per hour as compared with stationary performance under similar ambient conditions. Since, at present, these vehicles appear to have considerable leakage, Fig. 36 was prepared to show the additional heat load above the transmission heat gain due to air leakage at various ambient conditions, when the trailer interior is at OF. For this graph it was assumed that all air entering the trailer would leave saturated at OF.

HEAT LOAD DUE TO AIR LEAKAGE, TRAILER TEMPERATURE 0°F (LESS TRANSMISSION LOAD)

FIGURE 36
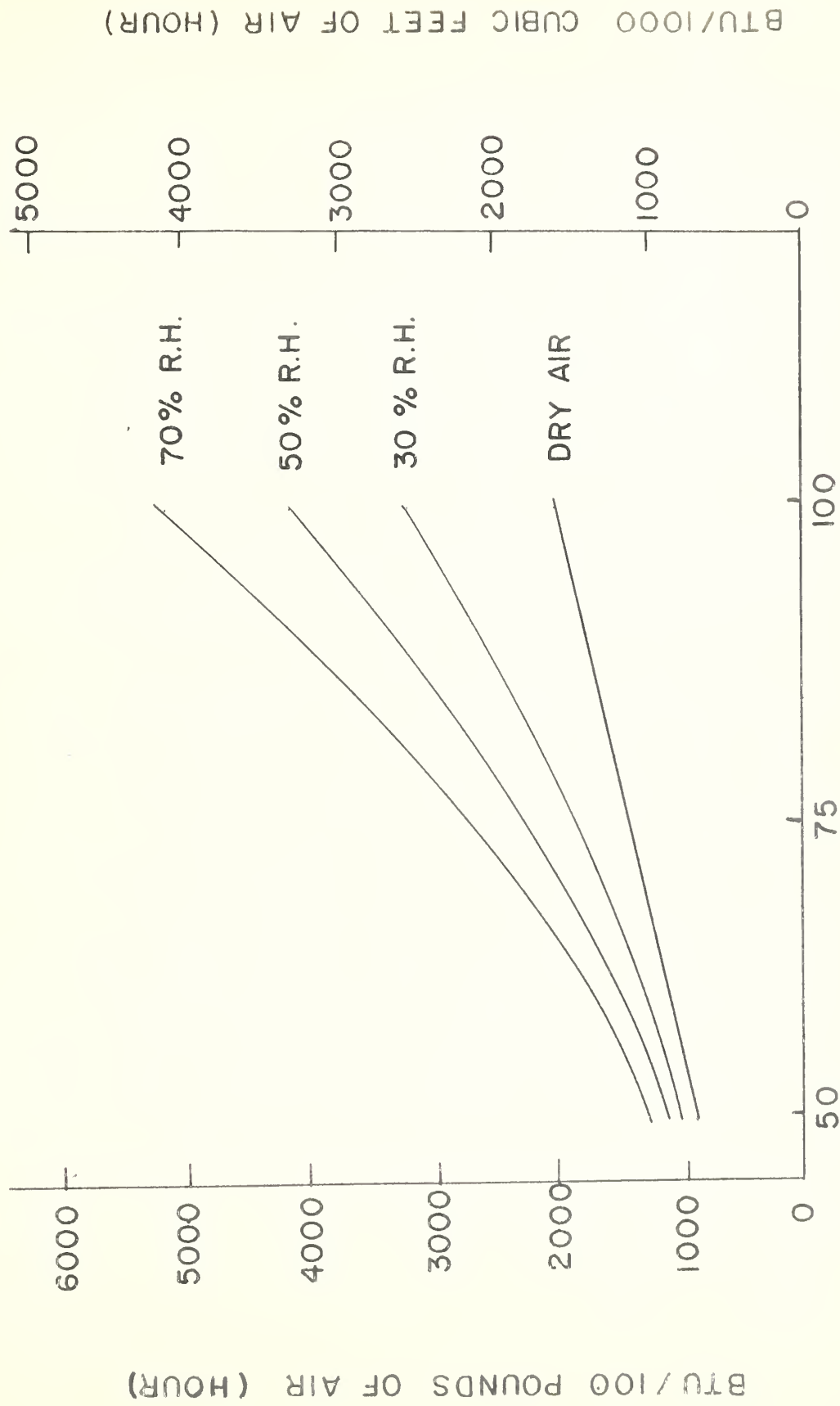
8. Discussion and Conclusions

The tests made of three commercial trailers in the laboratory and on the road and the air leakage and pressure distribution studies made on three military trailers indicate the following conclusions.

1. The heat gain of a refrigerated trailer is significantly greater during road operation at 50 mph than under stationary laboratory conditions for the same conditions of ambient temperature and humidity. This increase ranged from about 20 to 30 percent for the three commercial trailers tested at ambient conditions of 100F dry bulb temperature and 50 percent relative humidity. The extrapolated heat gain values for these conditions ranged from 9000 Btu/hr to 12,600 Btu/hr for a road speed of 50 mph.

2. The increase in heat gain on the road is due principally to air leakage into the trailer construction under the impact pressure of the ram air although small increases are caused by solar radiation and the movement of engine heat under the floor of the trailer.

3. The minimum air leakage rates for the three commercial trailers at a road speed of 50 mph were 970, 1590, and 860 cu ft/hr and may have been somewhat greater than these amounts. The corresponding computed heat gains due to air leakage at ambient conditions of 100F and 50 percent R.H. would be 3070, 5030, and 2730 Btu/hr respectively assuming that the leakage air left the trailer saturated at 0F. This latter assumption should be further studied as a part of a larger analysis of air and moisture movement in insulated structures. On this basis, the heat gain due to air leakage ranged from 32 percent to 69 percent of the heat transmission loss at a road speed of 50 mph under design test conditions. These percentages indicate the significant reductions possible in heat gain by eliminating air leakage in trailer bodies. The air leakage and ice accumulation in the trailers were not negligible under stationary conditions. The air leakage amounted to 235, 715, and 395, cu ft/hr and the ice accumulation rates averaged 0.32, 0.98, and 0.54 lb/hr respectively during the laboratory tests.

4. The effects of solar radiation on a trailer are largely nullified by the rapid air motion over the vehicle at a road speed of 50 mph. In a typical test in bright sunshine,

incident solar radiation raised the surface temperature of the
roof and one side of the trailer about 7.5°F above ambient
air temperature at this road speed. On a weighted average
basis this corresponded to approximately three degrees rise in
temperature for the entire exterior surface. Under stationary
conditions the roof temperature could be increased 25 degrees
or more by solar radiation.

5. The under side of the trailer was heated as much
as 15 degrees above ambient temperature in some cases during
road operation, principally by waste heat from the tractor
engine. On a weighted average basis this may not represent
more than three degrees rise in temperature for the entire
trailer surface. This would not cause a very large increase in
overall heat gain of the trailer, but could significantly
affect the preservation of food on the interior floor of the
trailer, if chilled air were not circulated around and under
the load.

6. Ram air pressures up to 1.25 in. W.G. will occur
on the nose of a trailer at a road speed of 50 mph on the
portions unshielded by the tractor, although the average ram
pressure is probably considerably below this value. The
static pressures in the cargo space, in the insulation space,
and over most of the exterior skin surface (excluding the
nose) were about equal and ranged from 0.2 to 0.4 in. W.G.
below atmospheric pressure for road speeds of 50 mph. The
leakage air probably enters the trailer body primarily on the
nose of the trailer and leaves the body over the remainder of
the surface, leaving most of the moisture in the ambient air
deposited as ice in the insulation space.

7. The exterior skins of the commercial trailers
tested leaked considerably. Under laboratory test conditions
the stack effect tending to cause leakage was only about
0.030 in. W.G., but the air leakage rates ranged from 235
to 715 cu ft/hr as indicated by the rate of weight gain of
the trailers. There was probably several times as much air
exchange between the insulation space and the outdoors as
between the cargo space and outdoors.

8.   The results of these studies show that a labora-
tory rating method for refrigerated trailers needs to incor-
porate some means for taking into account the air leakage that
will occur on the road with present types of body construction.

9.   The results further suggest that smaller
refrigerating units could be used if air leakage could be
eliminated, or alternately, less insulation might be required
if air leakage were significantly reduced. It is also probable
that the deterioration of trailer bodies would proceed more
slowly if moisture could be kept out of the insulation spaces.

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Electricity and Electronics. Resistance and Reactance. Electron Devices. Electrical Instruments. Magnetic Measurements. Dielectrics. Engineering Electronics. Electronic Instrumentation. Electrochemistry.

Optics and Metrology. Photometry and Colorimetry. Optical Instruments. Photographic Technology. Length. Engineering Metrology.

Heat. Temperature Physics. Thermodynamics. Cryogenic Physics. Rheology. Engine Fuels. Free Radicals Research.

Atomic and Radiation Physics. Spectroscopy. Radiometry. Mass Spectrometry. Solid State Physics. Electron Physics. Atomic Physics. Neutron Physics. Nuclear Physics. Radioactivity. X-rays. Betatron. Nucleonic Instrumentation. Radiological Equipment.

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Mechanics. Sound. Mechanical Instruments. Fluid Mechanics. Engineering Mechanics. Mass and Scale. Capacity, Density, and Fluid Meters. Combustion Controls.

Organic and Fibrous Materials. Rubber. Textiles. Paper. Leather. Testing and Specifications. Polymer Structure. Plastics. Dental Research.

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Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics.

Data Processing Systems. SEAC Engineering Group. Components and Techniques. Digital Circuitry. Digital Systems. Analog Systems. Application Engineering.

• Office of Basic Instrumentation.   • Office of Weights and Measures.

BOULDER, COLORADO

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Radio Propagation Engineering. Data Reduction Instrumentation. Modulation Systems. Navigation Systems. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Radio Systems Application Engineering. Radio Meteorology.

Radio Standards. High Frequency Electrical Standards. Radio Broadcast Service. High Frequency Impedance Standards. Calibration Center. Microwave Physics. Microwave Circuit Standards.